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REPORT 600

Human Factors Guidelines for Road Systems

Second Edition

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Mark S. Bush
Staff Officer
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This report completes and updates the first edition of *NCHRP Report 600: Human Factors Guidelines for Road Systems* (HFG), which was published previously in three collections. The HFG contains guidelines that provide human factors principles and findings for consideration by, and is a resource document for, highway designers, traffic engineers, and other safety practitioners. Each of the design guidelines in the HFG is presented using a consistent, highly structured format that is intended to maximize ease-of-use and interpretability. The guidelines focus on providing specific, actionable design principles, supported by a discussion and review of key research and analyses. Special design issues and considerations are included to help address design constraints and relevant trade-offs.

The TRB, AASHTO, and the FHWA have been working since 2001 on successive and complementary projects that together help promote increased safety for all road users. The results of these efforts are the *Highway Safety Manual* (HSM) and the *Human Factors Guidelines for Road Systems* (HFG). From 2008 through 2010, various completed chapters of the HFG were published in three collections; this report concludes the last project, includes the remaining chapters, and provides the entire compilation as a new holistic publication. These projects have been supported by funding from NCHRP and the FHWA. The HSM and the HFG promote improved safety for highway users and complement each other. While the HSM includes one section of a chapter on human factors, it provides only a broad scope and not guidelines. Each should be used together; however, neither document is a substitute for national or state standards such as *A Policy on Geometric Design of Highways and Streets* (the AASHTO Green Book) or the *Manual on Uniform Traffic Control Devices* (MUTCD).

The HSM provides highway engineers with a synthesis of validated highway research and proven procedures for integrating safety into both new and improvement projects. It also provides practitioners with enhanced analytic tools for predicting and measuring the success of implemented safety countermeasures. The HSM can be used to develop possible design alternatives to improve safety on an in-service or planned intersection or section of roadway; the HFG can be used concurrently to identify design solutions or to enhance the alternatives suggested by the HSM.

The HFG is a new roadway design resource that provides data and insights from the scientific literature on the needs, capabilities, and limitations of road users, including perception and effects of visual demands, cognition and influence of expectancies on driving behavior, and individual differences including age and other factors. The HFG provides guidance for roadway location elements (e.g., curves, grades, intersections, construction/work zones, rail-highway grade crossings) and traffic engineering elements (e.g., signing, changeable message signs, markings, and lighting). In addition, the HFG provides tutorials on special design topics, an index, and a glossary of technical terms.

Successful highway safety depends on the consideration and integration of three fundamental components—the roadway, the vehicle, and the roadway user. Unfortunately, many traditional resources used by practitioners lack data on the information needs, limitations, and capabilities of roadway users. Because driver error is a key contributor to driving crashes and road fatalities, a more driver-centered approach to highway design and operation will promote improved highway safety. The easy-to-use guidelines in the HFG provide the highway designer and traffic engineer with objective, defensible human factors principles and information that can be used to support and justify design decisions. To this end, the HFG is a valuable tool in providing information about how road users operate in the driving environment. There is great value in bringing road users' needs, capabilities, and limitations in to roadway design and traffic engineering.

NOTES ON PUBLICATION OF *HUMAN FACTORS GUIDELINES FOR ROAD SYSTEMS, SECOND EDITION*

The first edition of *NCHRP Report 600: Human Factors Guidelines for Road Systems* was published in three collections from March 2008 to July 2010. This self-contained second edition contains new Chapters 7, 8, 9, 12, 14, 15, 21, and 27 and minor updates to the remaining chapters.

Chapter 3 (Finding Information Like a Road User) and Chapter 4 (Integrating Road User, Highway Design, and Traffic Engineering Needs) are authored by Samuel Tignor, Thomas Hicks, and Joseph Mondillo.

Chapter 5 (Sight Distance Guidelines) and Tutorials 1 and 2 in Chapter 22 (Tutorials) present a revision of materials originally published as *NCHRP Web-Only Document 70: Comprehensive Human Factors Guidelines for Road Systems* (2004), N. Lerner, R. Llaneras, A. Smiley, and F. Hanscom, Washington, DC: Transportation Research Board.

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PART I Introduction

* See "Notes on Publication of *Human Factors Guidelines for Road Systems, Second Edition*" on facing page.

PART III Human Factors Guidance for Roadway Location Elements

PART I

Introduction

CHAPTER 1

Why Have Human Factors Guidelines for Road Systems?

1.1 Purpose of Human Factors Guidelines for Road Systems

The purpose of *Human Factors Guidelines for Road Systems* (HFG) is to provide the best factual information and insight on the characteristics of road users to facilitate safe roadway design and operational decisions.

A number of existing guides, standards, and references are available to facilitate safe roadway design and operational decisions, including *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2011), the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA, 2009), and the *Highway Safety Manual* (HSM) (AASHTO, 2010). However, these materials often lack a substantive presentation and discussion of human factor principles and concepts that could be used by highway designers and traffic engineers to improve roadway design and traffic safety. Despite a widespread acknowledgement that traffic safety reflects the consideration and integration of three components—the roadway, the vehicle, and the roadway user—the information needs, limitations, and capabilities of roadway users are often neglected in traditional resources used by practitioners. In short, existing references applicable to road system design do not provide highway designers and traffic engineers with adequate guidance for incorporating road user needs, limitations, and capabilities when dealing with design and operational issues.

The *Human Factors Guidelines for Road Systems* is intended to provide human factors principles and findings to the highway designer and traffic engineer. It will allow the non-expert in human factors to more effectively bring consideration of the road user's capabilities and limitations into the practice of design, operations, and safety. The HFG serves as a complement to other primary design references and standards. It does not duplicate or replace them. It is an additional tool for the engineer to use in designing and operating roadways that are safely usable by the broad range of road users.

1.2 Overview of the HFG

This document provides practitioners who design and operate streets and highways with relevant human factors data and principles, in a useful guideline form. The ITE *Traffic Engineering Handbook* (Pline, 1999) cites a definition of "traffic engineering" as "that branch of engineering which applies technology, science, and human factors to the planning, design, operations and management of roads, streets, bikeways, highways, their networks, terminals, and abutting lands." Thus the discipline of human factors is recognized as an integral contributor to traffic engineering practice. Many highway designers and traffic engineers, however, do not have a clear understanding of what human factors is and how its principles are relevant to their work.

Human factors is an applied, scientific discipline that tries to enhance the relationship between devices and systems, and the people who are meant to use them. As a discipline, human factors approaches system design with the "user" as its focal point. Human factors practitioners bring expert knowledge concerning the capabilities and limitations of human beings that are important for the design of devices and systems of many kinds. There has been a number of elements within the field of transportation engineering that have benefited from human factors research, including sight distance requirements; work zone layouts; sign design, placement, and spacing criteria; dimensions for road markings; color specifications; sign letter fonts and icons; and signal timing.

Basic crash statistics in the United States highlight the importance of human factors to road system design. In 2001, for example, there were more than 6 million police-reported (and many more non-reported) collisions in the United States, with attendant loss of life, property, and productivity (NHTSA, 2002). Furthermore, some form of driver error was usually a contributing factor in nearly half (approximately 44%) of the crashes leading to a fatality. "Error" means the road user did not perform his or her task optimally. Misperceptions, slow reactions, and poor decisions are the products of a poor match between the needs and capabilities of drivers and the task demands that they face on the roadway. A more driver-centered approach to highway design and operation will promote continued improvements in highway safety.

While many roadway design practices are based on extensive, well-documented, and fully appropriate behavioral data, this is not always the case. Some design practices recommended by existing standards and guidance can include the following limitations:

- They do not have any empirical basis and/or have not been formally evaluated for adequacy for road users.
- They are based on outdated data that may no longer be representative of current driver behaviors.
- They are based on overly simple models of what road users see or do.
- They are based on incorrect assumptions about road users' capabilities and limitations.
- They do not reflect recent changes in communications technology, vehicle features, roadway features, roadside environment, traffic control devices, or traffic operational characteristics.
- They do not reflect the special needs of some road users, such as older drivers, visually impaired pedestrians, pedestrians with mobility limitations, heavy truck operators, and users of lower-speed alternative transportation devices.
- They do not adequately address trade-offs between conflicting demands that are related to important road user characteristics.
- They may not address specific combinations of roadway design features that can have an impact on road user behavior and subsequent safety.

The HFG provides guidance based on empirical data and expert judgment without the above limitations.

CHAPTER 2

How to Use This Document

2.1 Organization of the HFG

This document is divided into five parts. Part I, Introduction, is a short introduction to the document. The first chapter explains why having human factors guidance is useful. This second chapter explains how to use the document and take advantage of its features.

Part II, Bringing Road User Capabilities into Highway Design and Traffic Engineering Practice, describes a human factors approach to roadway design, presents basic principles and methods, and provides key information about basic road user capabilities. Part II is about road users and how to take their needs into account. It is the basis from which the guidance in Parts III and IV is derived.

Parts III and IV present the actual guidance statements within this document. Part III, Human Factors Guidance for Roadway Location Elements, is organized around specific roadway location elements, such as signalized intersections and work zones. Part IV, Human Factors Guidance for Traffic Engineering Elements, deals with traffic engineering elements such as fixed signage, variable message signs, markings, and lighting. The guidance among many of these chapters is interrelated and the chapter sections link to one another.

Part V, Additional Information, presents tutorials (see Section 2.4) and collects other information that may be useful when using the HFG.

2.2 Scope and Limitations of the HFG

The HFG is intended to serve a number of important purposes. Specifically, the HFG provides the following:

- An introduction to the field of human factors as it is applied to highway design and traffic engineering
- Guidance for more optimal design of highways and traffic control devices
- Information linking human factors data and analysis with related guidance in other key highway design and traffic engineering reference documents
- Help in solving problems related to road user considerations, including identifying probable human factors causes or countermeasures
- Objective, defensible information that can be used to support and justify design decisions

In addition, the HFG has some limitations. Specifically, the HFG is *not* the following:

- An alternative to primary design references in highway design and traffic engineering. It is intended to complement and amplify aspects of these other references, such as the

MUTCD (FHWA, 2009), *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2011), the *Traffic Control Devices Handbook* (Pline, 2001), the *Highway Safety Manual* (2010), and other guidance.

- A source for comprehensive design specifications nor a redundant treatment of other documents. The HFG is meant to add to, and refine, existing guidance.
- A textbook or tutorial on human factors or a comprehensive source of human factors literature.
- A guide to crash investigation or a comprehensive reference for safety diagnosis.

2.3 The Two-Page Format

In the HFG, a consistent two-page format is used to present the individual human factors guidelines provided in Chapters 5 through 21. On each page, the main issue being addressed by the guideline (e.g., When and How to Use Sight Distance Information, How to Diagnose Sight Distance Problems, etc.) is indicated by centered, bold type within the header. As described in more detail below, the left-hand page presents the title of the guideline; an introduction and overview of the guideline; the guideline itself; the rating associated with the guideline; and a graphic, table, or figure that augments the text information. The right-hand page provides the more detailed supporting rationale for the guideline that a highway designer or traffic engineer may need in order to perform his or her day-to-day design tasks, as well as special design considerations, cross-references to related guidelines, and a list of key references. A sample guideline, with key features highlighted, is shown in Figure 2-1; a detailed description of the presentation format of the guidelines follows.

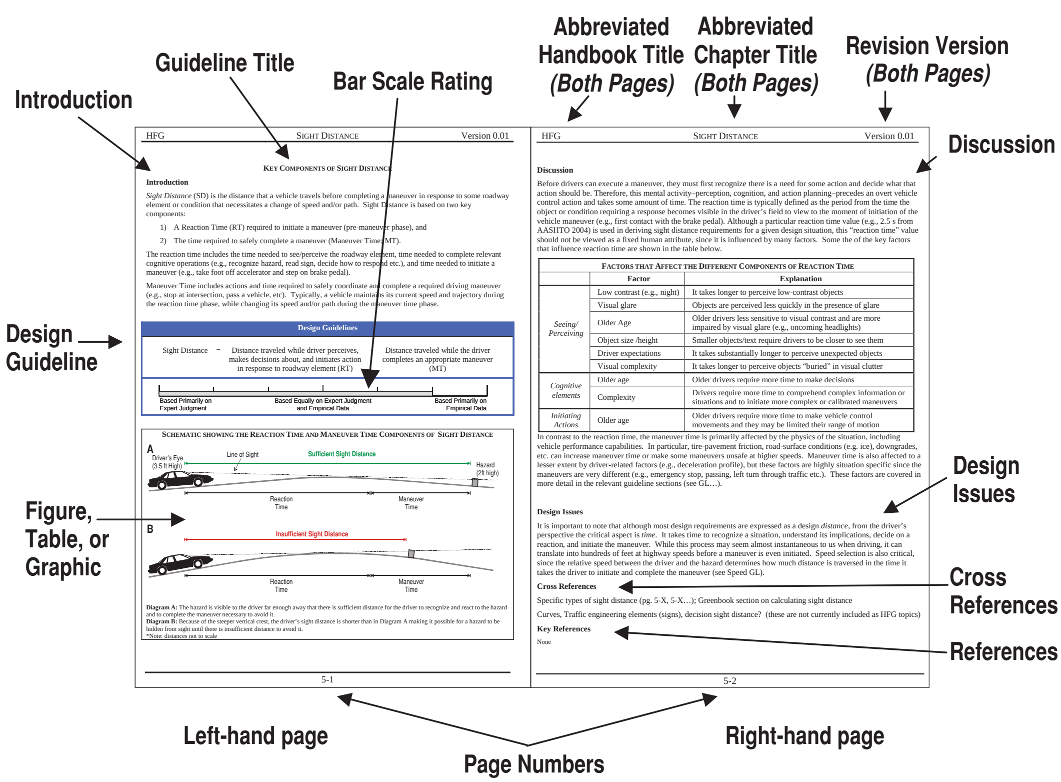


Figure 2-1. Guideline format used in the HFG.

2.3.1 The Left-Hand Page

The guideline title is indicated by centered, bold type at the top of the left-hand page.

2.3.1.1 Introduction

This subsection briefly defines the guideline and provides basic information about the roadway design parameter and the guideline. For example, this subsection might be used to provide the unit of measurement (e.g., visual angle, meters, foot-lamberts) for the guideline or to provide equations for the derivation of certain parameters.

2.3.1.2 Design Guideline

This subsection presents a quantitative guideline (when possible), either as a point value, a range, or an explicit recommendation. The guideline is always presented prominently and is enclosed in a blue box that is centered on the page.

In some cases, the guideline is presented qualitatively in general terms (e.g., "If the operating speed of a roadway is substantially higher than the design speed, then it may be appropriate to increase sight distance for higher traveling speeds."). However, in most cases, the design guideline is presented quantitatively (e.g., "The reaction time component of stopping sight distance can be expected to be **1.6 s** under good-visibility, good-traction conditions.").

2.3.1.3 The Bar-Scale Rating System

For some design topics, enough empirical data exist to provide well-supported guidelines, and the use of expert judgment is minimal. For others, empirical data have provided only the foundation for a decision about what the guideline should be, but experience and judgment have been used to determine the final guideline. For yet other topics, little or no empirical data were available, and the guideline was based primarily on expert judgment.

To aid highway designers and traffic engineers in making design trade-offs, individual guidelines have been rated according to the relative contribution that empirical data and expert judgment have each made to the guideline. Specifically, each guideline has been rated along a continuum, with each guideline falling somewhere between "Based Primarily on Expert Judgment" and "Based Primarily on Experimental Data." These terms are defined below.

Based Primarily on Expert Judgment. Little or no empirical data were used to develop this guideline. Expert judgment and design convention were used to develop this guideline.

Based Equally on Expert Judgment and Experimental Data. Equal amounts of expert judgment and experimental data were used to develop this guideline. There may have been a lack of consistency in the research finding, requiring greater amounts of expert judgment. Or, research may have been lacking in this area, requiring the results of research from related content domains to be interpreted for use in this context.

Based Primarily on Experimental Data. The guideline is based on high quality and consistent data sources that apply directly to the guideline. Empirical data from highly relevant content domains (e.g., transportation human factors, driver performance data) were primarily used to develop this guideline. Little expert judgment was required to develop this guideline.

2.3.1.4 Figure, Table, or Graphic

This subsection provides a figure, table, or graphic to augment the guideline. This figure, table, or graphic provides "at-a-glance" information considered to be particularly important to the conceptualization and use of the guideline. It provides a visual representation of the guideline (or some aspect of the guideline) that may be difficult to grasp from the design guideline itself, which is quantitative and text based.

This figure, table, or graphic may take many forms, including a drawing depicting a generic application of a guideline or a particular design issue, a flowchart of measurement procedures for the guideline, a table that summarizes the guideline, or schematic examples of specific design solutions.

2.3.2 The Right-Hand Page

2.3.2.1 Discussion

This subsection briefly summarizes the rationale behind the choice of the guideline. In particular, the discussion explains the logic, premises, assumptions, and train-of-thought associated with development of the guideline. The focus is on a presentation of driver limitations and capabilities deemed relevant to the particular guideline topic. The discussion can take many forms, including a brief review of applicable empirical studies, references to traditional design practice, or an analysis of relevant information.

The discussion is presented primarily to help HFG users understand the guideline and to help them explain or justify the guideline to other members of their respective development teams. Also, because these human factors guidelines are expected to be revised as additional empirical data become available, this subsection will be useful to future developers of the guidelines. In particular, the discussion will enable future guideline developers to determine how new information on road users' capabilities and limitations can (or should) be integrated into the existing guidelines.

For example, the design guideline "Determining Stopping Sight Distance" in Chapter 5 has been developed through consideration of experimental data gathered under a range of visibility (good and poor) and vehicle traction (good and poor) conditions. Thus, this guideline is presented as being the sum of driver reaction time plus vehicle deceleration, under a range of visibility/traction conditions. If new driver performance analyses or data for these conditions are obtained (or if new assumptions are made), future design guideline developers will be able to evaluate the quality and applicability of this new information relative to the discussion in the current design guideline "Determining Stopping Sight Distance" and determine what (if any) changes should be made to the design guideline.

2.3.2.2 Design Issues

This subsection presents special design considerations associated with a particular guideline. These special considerations may include design goals from the perspective of other disciplines (e.g., highway engineering, urban planning, physiology), interactions with other guidelines, special difficulties associated with the guideline's conceptualization or measurement, or special performance implications associated with the guideline.

2.3.2.3 Cross References

This subsection lists the titles and page numbers of other guidelines within the handbook that are relevant to the current guideline.

2.3.2.4 References

This subsection lists the references associated with the formulation of the guideline. Each of these references will have been assigned a reference number that was used to note it within the text of the design guideline (e.g., as part of the introduction, discussion, or design issues sections). A complete reference section is provided in Chapter 23 of this document.

2.4 Tutorials

Tutorials are provided in the HFG for important topics, special issues, and detailed procedures that cannot be addressed within the two-page constraints of individual guidelines.

2.5 Other Features

A Glossary is provided in Chapter 24. Technical words and phrases are defined in the Glossary and listed in the Index (Chapter 25). Abbreviations are provided in Chapter 26. Also, equations are numbered sequentially and listed separately in Chapter 27.

PART II

Bringing Road User Capabilities into Highway Design and Traffic Engineering Practice

CHAPTER 3

Finding Information Like a Road User

3.1 Introduction

Some people have said the primary decision-maker in the highway transportation system is the road user. But this statement is just not true. It is not true because many primary decisions are made before the road user ever sees and uses the road. During design and/or reconstruction, primary decisions include the magnitude of the vertical and horizontal alignment, the type of traffic control, and the vehicles permitted on the facility, among others; these decisions are made by highway designers and traffic engineers.

The purpose of this chapter is to remind users of the HFG that road users must read and comprehend from the roadway what the highway designer and traffic engineer intend for them to do. Unfortunately, the road users are not highway designers or traffic engineers and what they comprehend, while totally logical to them, may not be what the highway designers and traffic engineers intended. In short, this chapter illustrates that highway designers and traffic engineers must work together and serve as virtual road users if their goal is to maximize or improve highway safety. This chapter will show through examples why the highway designers and traffic engineers must jointly consider how their individual work may be interpreted by the road user and whether that interpretation promotes user safety.

3.2 Road User as a Component of the Highway System

Highway systems have three major components: the road, traffic control, and users with or without a vehicle (Figure 3-1). For the highway system to operate efficiently and safely, each of these components must work together as a combined unit. This task is not easy, largely because of the wide range of roadway environments, vehicles, and users. Highway systems are composed of local roads, collectors, arterials, and freeways—each having specific design features suitable for their environment. Vehicles using the roads vary widely with respect to weight, size, and performance. Vehicles using the roads may be small, light-weight vehicles with limited power; moderate-size and -powered vehicles; or large, heavy trucks with the horsepower to permit high speeds. Also, the population of road users includes car and truck operators, pedestrians, motorcycle operators, and bicycle riders, all, sometimes, with some degree of physiological disability.

If the goal is to provide highway travel for road users that is both safe and operationally efficient, the needs and constraints of highway design, traffic control, and users must be successfully integrated. Together they must perform as one—not a group of three. Highway designers must know the impact of their design decisions and how they will affect the control needs of traffic engineers as well as the resulting impact they will have on users in performing efficiently and

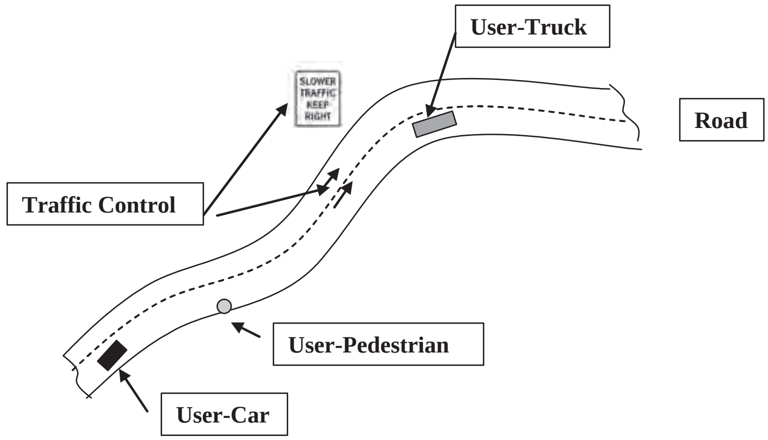


Figure 3-1. Example components of the highway system.

safely. Traffic engineers cannot be expected to solve design problems with traffic engineering fixes. Safe roads are those that are self-explaining where users know how to behave solely because of the design and control of the road (Theeuwes & Godthelp, 1992).

Road users cannot be expected to solve either highway design or traffic engineering problems without making mistakes and/or compromising operational efficiency and safety. Highway system failure in the United States can be measured by the 42,000 fatalities, 3 million injuries, 6 million police-reported crashes, and many more unreported crashes that occur annually (NHTSA, 2004). System failures can be attributed to errors by drivers, design, traffic control, and combinations of these factors (Hauer, 1999).

Design and operation solutions must be jointly developed by highway designers and traffic engineers with both totally aware and cognizant of the needs and limitations of all road users. In effect, they must incorporate into their joint solutions human factor principles that are in keeping with the needs of all users.

3.3 Example Problems of Highway Designers and Traffic Engineers

The following examples illustrate typical design and operational problems where consideration of good human factor principles is appropriate.

- An intersection with the crossing road at an acute angle (30°) has experienced an unusually high number of crashes. See Figures 3-2 and 3-3. The county supervisors have asked the local highway agency for a review and recommendation on what should be done to correct the problem. After reviewing the site, the current and projected traffic flow, and the expected land development in the area, the agency recommended the intersection be changed. Options considered included using stop control on each approach, signalization, and redesign. Neither all-way stop control nor signalization met the MUTCD warrants; therefore, they were discarded as options (FHWA, 2009). Research literature indicates that drivers have difficulty estimating gap size and speed of approaching vehicles at intersections where intersecting roads are not within about 25° of normal (Pline, 1992). The recommended solution was to redesign the crossing road approach to eliminate the acute angle so the approach would be nearly perpendicular to the major road.

Figure 3-2. Northbound approach to example intersection.

- Each end of a 1-mi section of two-lane road in a suburban area had been improved to a four-lane divided highway. The remaining two-lane road had very bad vertical curvature and a cross section with very narrow shoulders; thus the two-lane road environment was very different from either the upstream or downstream road sections. The speed limit was 40 mi/h within the two-lane section and the newer four-lane sections. The two-lane section seemed to have a higher than normal number of crashes. The highway agency requested that the safety, design, and traffic engineers review the roadway and provide recommendations on what should be done. The crash occurrence during the day was found to be not unusually high. At night, however, this was not the case. Drivers approaching the sharp, vertical crests were running off of the road and hitting roadside objects. The engineers recommended that advance curve warning signs, vertical delineators, and roadway lighting be installed in the two-lane section to help prevent drivers approaching crests at night from being overcome by sudden glare produced by opposing vehicles previously hidden in the sags as shown in Figure 3-4.

Figure 3-3. Westbound approach to example intersection.

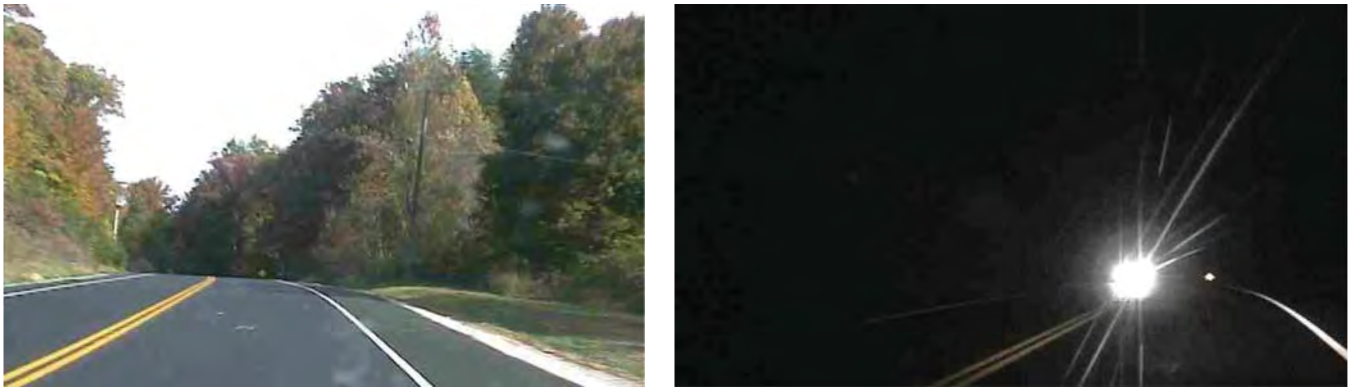


Figure 3-4. Day and night views of approaching crest.

Some human factor characteristics regarding roadway users are available to help implement preferred design and control solutions. The following are some of those found in the research literature:

- Drivers experience difficulty at intersections in estimating gap size and speed of approaching vehicles (Staplin, Lococo, & Byington, 1998).
- Drivers experience problems in detecting a sharper curve after negotiating several longer radius curves (Glennon, 1996).
- Additional distance and time are required to slow or stop under adverse weather conditions (Baerwald, 1965).
- Excessive messages on changeable message signs (CMSs) can inhibit correct decisions and traffic flow, and safety (Staplin et al., 1998).
- Bright light sources, whether from vehicles or roadside property, can cause glare, user-blinding, and possible loss of vehicle control (Ogden, 1996).

While the previous items and two examples are not an exhaustive list, they illustrate a few of the many user problems encountered. Highway designers and traffic engineers must be aware of such human factor characteristics and use them in a way that will improve or optimize the safety of the road system they are designing and controlling.

3.4 How Road Users Seek Information

Theeuwes and Godthelp (1992) have described self-explaining roads as road environments where users know how to behave based on the road design. Unfortunately, many roads today are not self-explaining. Self-explaining roads induce user behavior based on the design and not on "external agents" like signs and traffic signals. When the road is not self-explaining, highway operations can be inefficient, delayed, and unsafe, plus user speeds are more varied. Road users continuously seek information under many different conditions—from when the road environment has few vehicles or other users present to when many vehicles and other users are present; however, road users' access to information may be more difficult under conditions of darkness, inclement weather, glare from sunlight, etc. According to research findings, users categorize roads during their driving task and formulate their temporal reactions based on previously learned behavior (Theeuwes & Diks, 1995). Design standards by functional classification enhance user-learned behavior and their system expectations.

Road users seek information for navigation, guidance, and control (Alexander & Lunenfeld, 1990). Navigation information relates to getting from point A to B; guidance information relates to lane selection; and control relates to selection of vehicle speed, level of braking, and steering. The information road users seek varies according to the situation—sometimes complex and sometimes simple.

How road users seek information is fairly simple. They scan the road environment seeking the most meaningful information (MMI) needed for that particular road location and point in time. How they scan the environment depends on the presence or absence of potentially hazardous situations as they perceive them. Road users are generally alert for both longitudinal and lateral hazards (i.e., other vehicles, pedestrians, animals, or objects near their planned path); they develop an expectancy of the roadway based on what they previously experienced upstream. They seek the information they need by searching the road environment in front of, behind, and to the sides of the vehicle they are driving. This searching and scanning process is continuous for the duration of the trip.

Scanning of the road environment is a time-based activity. The speed at which scanning is performed is not constant but it is a function of the road environment (i.e., geometric design, vehicle speed, cross section elements, traffic volume, weather, vehicle mix, presence of pedestrians, driver experience, traffic control, etc). If the environment has no threatening activity perceived by the road user, the scanning rate may be slower, and he or she may have time for scenic pleasures. At other times the visual scanning rate may be greater because of enhanced road environment activity. Early notable research on driving scanning was conducted by Mourant, Rockwell, and Rackoff (1969).

Road users can receive and process only a finite amount of information in a short time period, not an infinite set of information. To describe perception-reaction time (PRT), Johannson and Rumar (1971) use a scale ranging from 0 to 6 bits of unexpected and expected information that a road user can process per second. They found the average driver processes about 1 and 1.5 bits of information per second for unexpected and expected situations, respectively. The more difficult or competing tasks a road user is confronted with, the longer he/she will take to select the response to initiate; also, not all road users perform the same (Johannson & Rumar, 1971). According to AASHTO, for unexpected situations some drivers take as long as 2.7 seconds (AASHTO, 2011). Therefore, highway designers and traffic engineers must plan and develop the road environment temporally and in accordance with the scanning ability of the road users.

Highway designers and traffic engineers often use distance-speed criteria (i.e., stopping distance, passing distance, intersection sight distance) to specify road design elements and placement of traffic control devices, but distance criteria are always based on time and how road users use it.

3.5 Examples of User-Scanned Road Environments

The purpose of this section is to illustrate the features that road users would classify as the MMI for making their next driving decision using a photograph of an example location. This kind of research is useful to highway designers and traffic engineers because it identifies what information road users are using and whether the individual bits of information are useful, competing, or potentially misleading to road users' decision making and safety.

The following examples were prepared by showing subjects hard copies of the roadway scenes, some with approaching vehicles and some with no approaching vehicles (Tignor, 2006). The subjects were asked to identify the most important information they would consider should they confront that situation when driving. A color code was used to prioritize the information from most to least important. The priority of the color code was from left to right with dark green as priority one. The road is in a suburban environment and it has a speed limit of 35 mi/h.

3.5.1 Example 1, View 1

The first example illustrates what subjects identify as MMI when there is a lot of activity in the road environment. As shown in Figure 3-5, when no vehicles are moving toward the road users (middle photograph), many items are identified as possible sources of meaningful information even though the road environment has many parked vehicles, three intersections, and a distant curve.

The presence of approaching vehicles (bottom photograph) changes what road users consider as important information. Approaching vehicles clearly induce the road users to concentrate their attention to them as sources of MMI. The items having the highest frequency of visual sources of meaningful information are approaching vehicles, the nearest intersections, and a distant curve.

3.5.2 Example 2, View 4

The second example illustrates how road users are adversely affected when roadway design and traffic control features are not appropriately coordinated. Figure 3-6 shows drivers approaching a very short vertical curve (top photograph) that has the potential of hiding downstream vehicles just beyond the crest of the curve. Just upstream of the crest is a speed limit sign.

The colored circles in the figure (middle and bottom photographs) show that many of the subjects look to the speed limit sign as the first or second most meaningful source of information as opposed to the crest beyond, which could hide a vehicle or other hazard in the roadway. They look at the speed limit sign whether a vehicle is or is not ahead of them. The short vertical curve is a roadway hazard, but the speed limit sign creates an additional hazard. If the road design and traffic engineering had been coordinated, more time would have been available for the road user to seek the MMI for assessing a potential conflict at the crest. From a safety perspective the speed limit sign should be relocated.

3.5.3 Observations from Examples

The previous two examples show some interesting results:

1. The selection process is different depending upon the presence or absence of other vehicles. When the roadway has no other vehicles in the forward view, the subjects' search is longitudinally and laterally broad and downstream from their current road location. They are primarily seeking information for guiding and controlling the vehicle.
2. When other vehicles are within their forward view, whether approaching or traveling in the same direction, the subjects' search is more selective. They tend to focus first on other vehicles in the road environment and second on information for guidance and control.
3. The examples illustrate how important it is for the road design and traffic control components to be coordinated to prevent competition for road user attention, which compromises user safety.

3.6 How Highway Designers and Traffic Engineers Work Together for Road Users

3.6.1 Serve as Virtual Road Users

Highway designers and traffic engineers must serve as virtual road users. They must view the route in small, incremental steps as if they were road users traveling downstream and gathering

1- Near Gordon Street

1 - Near Gordon Street

1t - Near Gordon Street

Figure 3-5. Example 1, View 1.

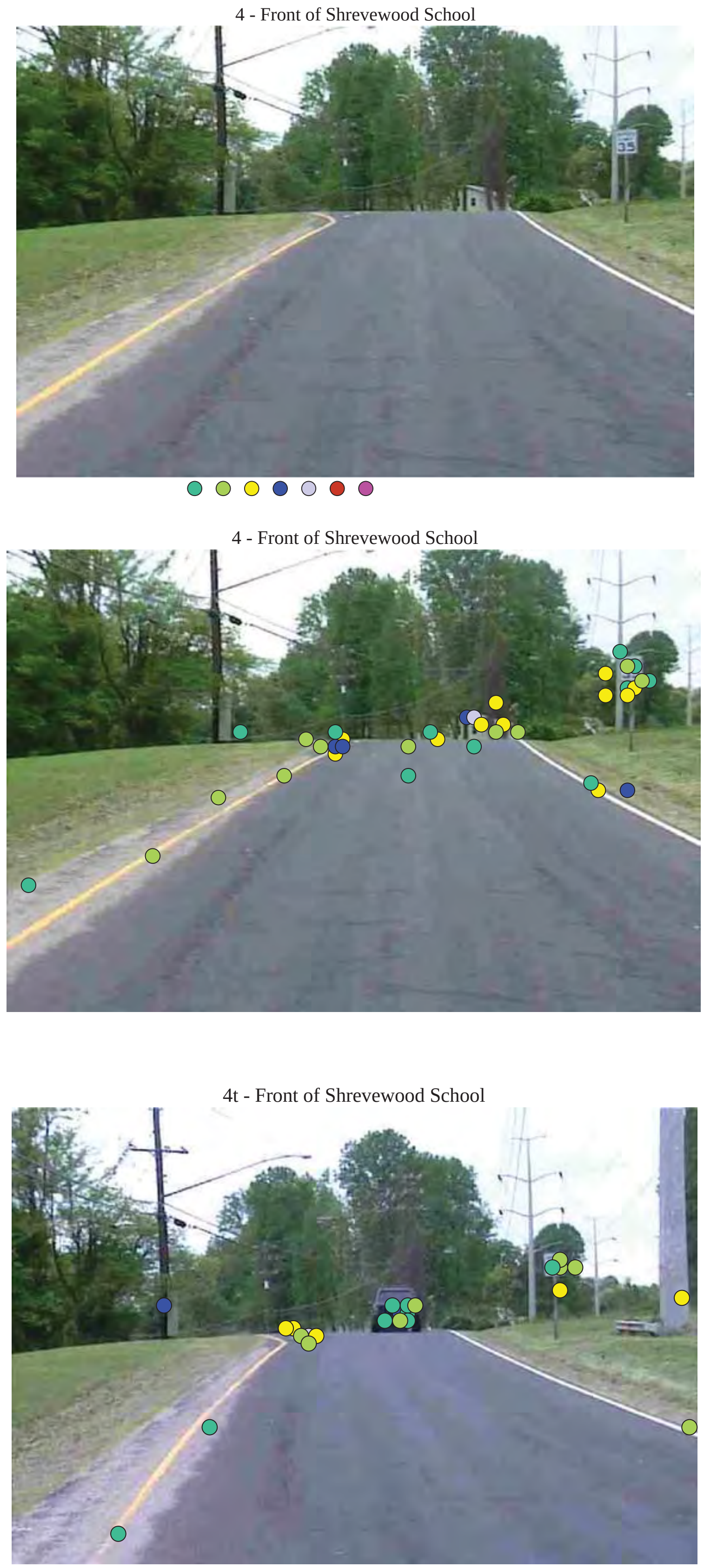


Figure 3-6. Example 2, View 4.

information in small time and space increments; they must learn from road users' experiences. Identifying what road users consider important is not easy.

Ninety percent of drivers' tasks are obtaining visual information from the roadway to maneuver their vehicle safely (Hartman, 1970). This visual information cannot be confusing and it must be complete and accurate if safe decisions are to be made. Road safety audits and a procedure used by McGee called SLIDE (Simplified Location of Information Deficiencies) depend on professional staff to identify safety problems associated with on-road design and traffic control applications and omissions (Morgan, 1999; McGee, Hughes, & Hostetter, 1986). The MMI procedure obtains information directly from road users about what in the road environment they consider important to their driving decisions. User input is important because 27% of road crashes are attributed to a joint association of road user and roadway environmental problems (Schlegel, 1993).

Eye scanning technology, in both real and simulated conditions, has also been used for obtaining information on what drivers view in the visual field. Although vast and time consuming to decipher, eye scanning data are interesting. The literature reports on search patterns of novice and experienced drivers (Mourant & Rockwell, 1972), the degrees of longitudinal and lateral eye fixation zones (Shinar, McDowell, & Rockwell, 1977), design of controls on vehicle instrument panels (Dingus, Antin, Hulse, & Wierwille, 1989), and signing (Smiley et al., 2005). For example, Mourant and Rockwell (1972) estimated 70% of driver eye pursuits were for lateral position. Shinar et al. (1977) found lateral eye movements increase during curve negotiation on two-lane roads and they begin 2 to 3 s before entering a curve. On right turns, drivers spend 55% of the time looking at the road and only 5% looking to the left. Similarly on left turns, drivers spend 38% of the time looking at the road and 24% of the time looking to the right. Recarte and Nunes (2000) found mean horizontal visual fixation to be $\pm 0.5°$ from center with a $\pm 2°$ standard deviation and mean vertical visual fixation to be 1° below the horizon with a $\pm 1°$ standard deviation. Harbluk, Noy and Eizenman (2002) reported 80% of all driver fixations are within the central 15° of the visual field. Gordon (1966) reported that 98% of driver fixations fell on or near the road edge or centerline. He also reported drivers look about 6.5 ft from the right edge of the road when following a left curve, and about 9 ft from the right edge of the road when turning right. While these findings are interesting, the research analysts must infer or guess what items are really important to road users' driving decisions. Consequently, the results from eye scanning research have not been previously incorporated into design standards and guidelines.

Yet, highway designers and traffic engineers must identify jointly the important design and traffic control elements that are critical to road user decision making. They must identify potentially conflicting and misleading information whether it be geometric, traffic control, or the combination of both. The roadway environment created must provide continuous, clear information that the road user can interpret quickly, accurately, and safely.

3.6.2 Incorporate Substantive Safety and Self-Explaining Designs

A substantive safe road system must be created (Hauer, 1999). When a road system is properly created, potential errors will be prevented by elimination of the following:

- The unintended use of infrastructure
- Non-uniformity and inconsistency of design and traffic control applications
- Encounters with large differences in speed
- Uncertain driver behavior

Self-explaining designs create road categories that are recognizable by users and are appropriate for the following:

- Flow requirements (i.e., small to large volumes)
- Speed functions (i.e., slow to high speed)
- Access functions (i.e., local roads, collectors, arterials)

Lastly, self-explaining roads have the following characteristics:

- Road environments where road users know how to behave simply by the design
- Road types in keeping with road user expectations based on visual information obtained and object conspicuity
- A driving environment that is intuitive and transparent (Theeuwes & Godthelp, 1992)

3.6.3 Jointly Develop Road Systems

To achieve an acceptable level of system safety, highway designers and traffic engineers need to serve as virtual road users. They must place themselves in the shoes of the road user and consider what the road user will identify as most important both during day and night conditions. To identify the MMI, the highway designer and traffic engineer will together need to apply principles similar to those found in road safety audits (Morgan, 1999):

- Highway designers and traffic engineers must jointly develop and agree on the goals for the road system that will meet the objectives of the road agency but have the safety of users in the forefront.
- Highway designers and traffic engineers must jointly develop, review, and approve the design and operational plans for each project. The designs will be self-explaining to the road users and provide substantive safety for them.
- Whether projects are new construction, upgrades, or maintenance, highway designers and traffic engineers must jointly oversee the field work and make inspections as virtual road users before the start of new operations. If misleading individual or combined design and control features are found, they should be eliminated before the road is opened to traffic.

CHAPTER 4

Integrating Road User, Highway Design, and Traffic Engineering Needs

4.1 Introduction

The purpose of this chapter is to help highway designers and traffic engineers function as virtual road users. Not all road user situations are the same; some are more demanding than others. The different situations make the highway designer's and the traffic engineer's work more challenging, more intricate, and more demanding. They must consider the human factor characteristics of the user in conjunction with four major components: (1) the geometric design elements, (2) roadway and vehicle operations, (3) type of highway, and (4) the roadway environment. At any given location, the roadway user only has a finite amount of time to make decisions. Users, even with total visual attention, may not have sufficient time, under demanding real-time conditions, to extract as much information as desired. Sometimes road users must make choices about what information is processed. The scope of this chapter is to illustrate the breadth of the human factor considerations as magnified by the four major components and how highway designers and traffic engineers must integrate them all in safety-oriented solutions given the constraints of the road user. This chapter also shows, through examples, how on-road problems can be reviewed and improved by using the recommendations in Parts III and IV.

4.2 Iterative Review Steps to Achieve Good Human Factor Applications

4.2.1 Process

Whether driving, walking, running, or bicycle riding, road users continuously scan the downstream environment that they are entering (Robinson, Erickson, Thurston, & Clark, 1972). The scanning can be represented as shown in Figure 4-1.

In the figure, a vehicle is proceeding from left to right. At location or time *I,* the user observes the road environment and corresponding traffic conditions. He or she identifies the MMI at that point in time and space and assesses what guidance and control is needed (Tignor, 2006). The user implements that control and continues with it until scanning location or time *I*+1 when an information refresher is determined necessary. Any number of conditions could initiate the need for an information refresher. The following are typical examples that could induce a need for new information at *I*+1:

- The cross section may have an increase or decrease in the number of lanes.
- Downstream traffic may be slowing or stopping in the lane the user is traveling.

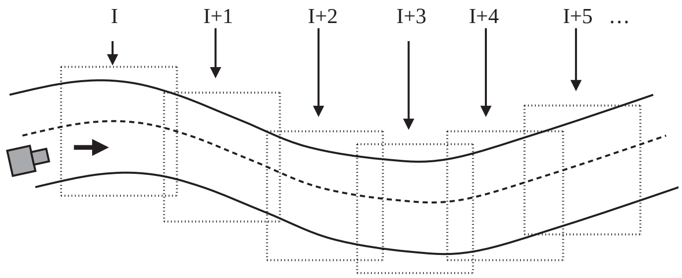


Figure 4-1. Road user scanning steps for finding most meaningful information (MMI).

- A pedestrian may be walking along the shoulder and without looking turn in front of the approaching user.
- Traffic may be entering the road from a side street or business establishment.
- A user is approaching a traffic sign with letters that are too small to read.
- A traffic signal is changing from green to amber.
- The road appears to be curving sharply to the right while the lane width is decreasing.

Each of these examples would necessitate that the road user reassess his or her information and control at *I* and determine if control modification is required. The challenge for virtual users (i.e., highway designers and traffic engineers) is to determine what kind of infrastructure modification is required, if any, from locations *I, I*+1, . . . *I*+*n.*

The scanning step sizes may vary and are influenced by the road user, type of operation, highway character, and environment. Some of these variables are listed in Table 4-1.

All road users are continuously sampling the road environment for information. The sampling rate can be represented as follows:

$$\text{Sampling Rate} = f\left(\text{user, operations, highway, environment}\right)$$

Table 4-1. Scanning step variables.

Factor	Variable	
User	Age Vision Experience	Cognitive ability Road familiarity
Operations	Speed Vehicle type Traffic volume	One-way flow Two-way flow Control type
Highway	Functional class Lane width Shoulder width Sight distance Pavement type and condition	Condition Roadside Grades Curvature
Environment	Weather Land use Pedestrians Urban	Rural Time of day Light condition Scenic/interest attractions

Through road scanning the user is updating his or her information database for making decisions. This process can be expressed as follows:

$$\text{Information}(t) = \text{Information}(t-1) + \text{changes during } \Delta t$$

Where

t = time
Δt = sampling interval

The real challenge then is to identify the changes that have occurred during the sampling interval (Δt). Changes include those elements detected by the road user within the visual scans or *I* steps. They may be previously seen items or new items not seen previously. The importance of the items may be elevated or reduced depending on their relationship to the user's need at the time (t). They may have a direct impact on the user's task of maintaining control of the vehicle or they may only serve as information useful for defining the approaching highway, operating, and environmental conditions.

4.2.2 Size of Iterative Steps

The highway designer and the traffic engineer must examine the road environment in incremental steps similar to those steps described in the previous section to ensure the road user will not be overloaded with temporal tasks and decisions. In short, good human factor principles must be integrated into the design of the road system.

The sizes of the iterative steps are not going to be the same for all road environments. They will vary depending on the road user, the type of highway, the operations, and the environment. The iterative steps, however, must overlap from one section to the next to ensure continuity of the travel path and that no potentially meaningful information for road users will be overlooked. The highway designers and traffic engineers must jointly examine the road environment—i.e., lane alignment (roadway and intersections), signing (advisory, regulatory and guidance), and operations (normal and work zones)—relative to the likelihood users will be able to perform the required tasks safely and efficiently within the time and space available.

Table 4-2 is a breakdown of some of the different steps taken by road users and their respective time restraints.

4.2.3 Identification of Potentially Conflicting or Missing Information

Identification of potentially conflicting, confusing, or missing information is probably one of the most important tasks of designers and traffic engineers. As virtual road users, designers and traffic engineers must examine the roadway environment for information conflicts that may mislead or confuse road users. They must anticipate what information the road user requires and where it is needed so appropriate design elements or traffic control can be integrated into the design and operational plans. Missing information is not helpful to the road user. In short, designers and traffic engineers must also seek road environments that are self-explaining, quickly understood, and easy for users to act upon (Theeuwes & Godthelp, 1992).

The example and analysis detailed in the next section illustrates problems that can be created by not properly relating the roadway geometrics to the traffic control. Together, designers and traffic engineers need to identify these problems when serving as virtual road users.

Table 4-2. Iterative steps used in sampling the road environment for information.

Step	Timing
Eye fixation time	• 0.20 to 0.25 s (Homburger & Kell, 1988) • 0.25 to 0.33 s (Mourant et al., 1969)
Turn head to the left	• 1.31 to 1.52 s (Mourant & Donohue, 1974)
Turn head to the right	• 1.09 to 1.14 s (Mourant & Donohue, 1974)
Car following	• Attention to lead vehicle reduces attention elsewhere by 15% (Mourant et al., 1969)
Sign detection	• Look time: 0.5 s (Zwahlen, 1995; Zwahlen & Schnell, 1998) • Saccade time: 0.03 s (Zwahlen, 1995; Zwahlen & Schnell, 1998) • Time for fixation on sign: 0.3 to 0.8 s (Zwahlen, 1995; Zwahlen & Schnell, 1998)
Sign reading	*Variable message signs* (Staplin et al., 1998) • Minimum exposure time:1 s/short word (four to eight characters) or 2 s/unit of information, whichever is larger • Reading time: 1 to 1.5 s/unit of information in light traffic • Minimum phase or page time: 3 s/page for a three-line message *Video signs* (Smiley et al., 2005) • 20% of glances to video signs exceeded 0.75 s • 38% of glances occurred when headways were less than 1 s • 25% of the glances were at angles greater than 20° • 76% of drivers looked ahead, 7% at signs and signals, 6% at pedestrians • Glances at video signs occurred with longer headways than with static signs
Use of mirrors	• 0.87 s, rear view (Mourant & Rockwell, 1972) • 0.98 s, left side (Mourant & Rockwell, 1972) • 0.78 s, rear view (Mourant & Donohue, 1974) • 0.88 s, left side (Mourant & Donohue, 1974)

4.3 Use of Parts III and IV for Specifying Designs

Parts III and IV are where explicit guidance statements are found. Before using the HFG for developing a solution to a problem, the HFG user must first study and understand the issues involved. For example, the illustrative example in section 4.3.1 involves both geometric design and signing issues. The approaching road users see a fork in the road and seven sets of signs communicating information to drivers. Because the signs are spaced too close together and the road is making an abrupt turn to the left, approaching drivers have insufficient time to scan the environment and make decisions on navigation, guidance, and control. Part III, Chapter 6, Curves, and Part IV, Chapter 18, Signing, are the sections of the HFG that will be used for developing the solution to this problem.

4.3.1 Detailed Description of Illustrative Example

A two-lane arterial roadway (US 293) crosses over a parkway (Route 6) that prohibits trucks. The arterial approaches the parkway from a tangent, but it then crosses over the parkway by curving sharply to the left. The connection to the parkway is a ramp that appears as a continuation of the arterial tangent. Because trucks are prevented from using the parkway, a sign directs them to an alternative roadway to reach the portion of Route 6 with unrestricted access. See Figure 4-2.

Figure 4-2. Improper signing and geometrics.

Various problems are found at this location:

- The alignment of the arterial and parkway ramp is not self-explaining. The first route marker shows Route 6 going to the right. The first word sign, on glance, suggests Route 6 is going to the left. The first line on the first word sign indicates the sign is for trucks and trailers, but that is not immediately clear to unfamiliar, approaching drivers. Car drivers also visually key on the sign. Confusion is created as to which road is Route 6, Route 293, and Route 9W.

- Because of the location of the signs and their close spacing, drivers have insufficient time to identify the important information. Also, the word signs have too many lines of information for users to read and interpret.
- The heights of the letters on the signs are too small.
- The message as to where trucks are permitted is not sufficiently clear.
- As seen by the skid marks near the gore in Figure 4-2 (bottom photograph), road users have difficulty in deciding whether to follow the road to the left or continue straight onto the ramp to the parkway.
- Access to intersecting routes or ramps should not appear to be a continuation of the approaching, main road.

Parts III and IV will be used together to develop a joint candidate design and control solution having a high level of road user acceptance, understanding, and safety. Candidate solutions must be in compliance with AASHTO design and MUTCD control standards (AASHTO, 2011; FHWA, 2009).

PART III

Human Factors Guidance for Roadway Location Elements

CHAPTER 5

Sight Distance Guidelines

KEY COMPONENTS OF SIGHT DISTANCE

Introduction

Sight distance (SD) is the distance that a vehicle travels before completing a maneuver in response to some roadway element, hazard, or condition that necessitates a change of speed and/or path. Sight distance is based on two key components:

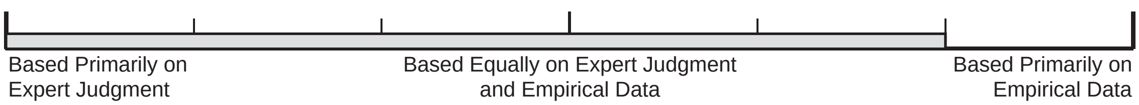
- The perception-reaction time (PRT) required to initiate a maneuver (pre-maneuver phase)
- The time required to safely complete a maneuver (MT).

The PRT component includes the time needed to see/perceive the roadway element, time needed to complete relevant cognitive operations (e.g., recognize hazard, read sign, decide how to respond, etc.), and time needed to initiate a maneuver (e.g., take foot off accelerator and step on brake pedal).

MT includes actions and time required to safely coordinate and complete a required driving maneuver (e.g., stop at intersection, pass a vehicle, etc.). Typically, a vehicle maintains its current speed and trajectory during the PRT phase, while changing its speed and/or path during the MT phase.

Design Guidelines

Sight Distance	=	Distance traveled while driver perceives, makes decisions about, and initiates action in response to roadway element (PRT)	+	Distance traveled while the driver completes an appropriate maneuver (MT)



SCHEMATIC SHOWING THE PERCEPTION-REACTION TIME AND MANEUVER TIME COMPONENTS OF SIGHT DISTANCE

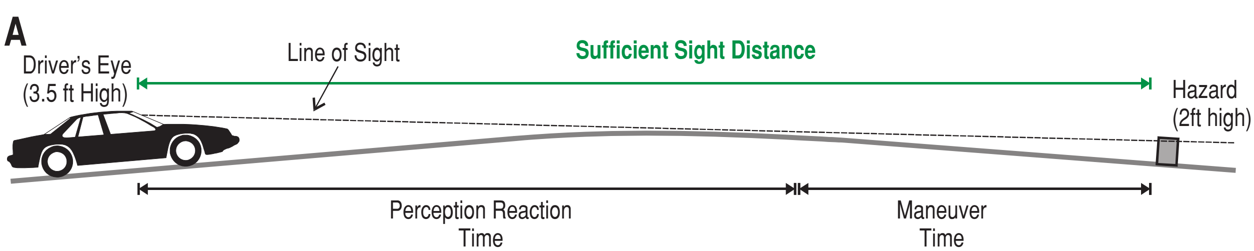


Diagram A: The hazard is visible to the driver far enough away that there is sufficient distance for the driver to recognize and react to the hazard and to complete the maneuver necessary to avoid it.

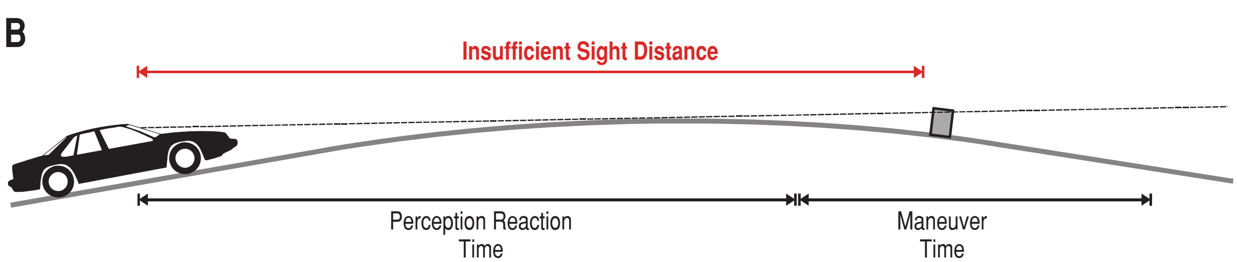


Diagram B: Because of the steeper vertical crest, the driver's sight distance is shorter than in Diagram A making it possible for a hazard to be hidden from sight until there is i*nsufficient distance to avoid it.*
**Note: distances not to scale*

Discussion

Before drivers can execute a maneuver, they must first recognize that some action is required and decide what that action should be. Therefore, this mental activity—perception, cognition, and action planning—precedes an overt vehicle control action and takes some amount of time. The PRT is typically defined as the period from the time the object or condition requiring a response becomes visible in the driver's field of view to the moment of initiation of the vehicle maneuver (e.g., first contact with the brake pedal). Although a particular PRT value (e.g., 2.5 s (*1*)) is used in deriving sight distance requirements for a given design situation, this PRT value should not be viewed as a fixed human attribute, because it is influenced by many factors. Some of the key factors that influence PRT are shown in the table below.

FACTORS THAT AFFECT THE DIFFERENT COMPONENTS OF PERCEPTION-REACTION TIME

Activity	Factor	Explanation
Seeing/ Perceiving	Low contrast (e.g., night)	Drivers take longer to perceive low-contrast objects.
	Visual glare	Objects are perceived less quickly in the presence of glare.
	Older age	Older drivers are less sensitive to visual contrast and are more impaired by visual glare (e.g., oncoming headlights).
	Object size/height	Smaller objects/text require drivers to be closer to see them.
	Driver expectations	Drivers take substantially longer to perceive unexpected objects.
	Visual complexity	Drivers take longer to perceive objects "buried" in visual clutter.
	Driver experience/familiarity	PRT to objects and situations will generally be faster with increased experience and/or familiarity.
Cognitive Elements	Older age	Older drivers require more time to make decisions.
	Complexity	Drivers require more time to comprehend complex information or situations and to initiate more complex or calibrated maneuvers.
Initiating Actions	Older age	Older drivers require more time to make vehicle control movements and their range of motion may be limited.

In contrast to the PRT, the MT is primarily affected by the physics of the situation, including vehicle performance capabilities. In particular, tire-pavement friction, road-surface conditions (e.g., ice), and downgrades can increase MT or make some maneuvers unsafe at higher speeds. MT is also affected to a lesser extent by driver-related factors (e.g., deceleration profile), but these factors are highly situation specific because the maneuvers are very different (e.g., emergency stop, passing, left turn through traffic, etc.).

Design Issues

Although most design requirements are expressed as a design distance, from the driver's perspective, the critical aspect is *time.* Time is required to recognize a situation, understand its implications, decide on a reaction, and initiate the maneuver. While this process may seem almost instantaneous to us when driving, it can translate into hundreds of feet at highway speeds before a maneuver is even initiated. Speed selection is also critical, because the relative speed between the driver and the hazard determines how much distance is traversed in the time required for the driver to initiate and complete the maneuver.

Cross References

Determining Intersection Sight Distance, 5-6
Determining When to Use Decision Sight Distance, 5-8
Determining Passing Sight Distance, 5-10

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington DC.

DETERMINING STOPPING SIGHT DISTANCE

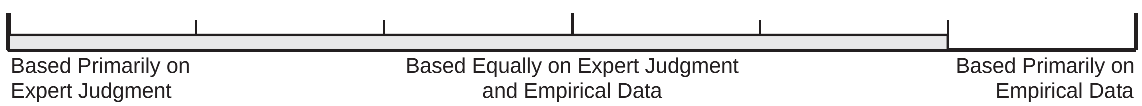
Introduction

Stopping sight distance (SSD) is the distance from a stopping requirement (such as a hazard) that is required for a vehicle traveling at or near design speed to be able to stop before reaching that stopping requirement. Stopping sight distance depends on (1) the time required for a driver to perceive and respond to the stopping requirement (PRT) and (2) how aggressively the driver decelerates (MT).

Design Guidelines

EQUATIONS FOR STOPPING SIGHT DISTANCE DESIGN VALUES

Metric	US Customary
$$SSD = 0.278Vt_{RT} + 0.039\frac{V^2}{a}$$ Where: t_{RT} = perception-reaction time V = design speed, km/h a = deceleration level, m/s^2 (see discussion)	$$SSD = 1.47Vt_{RT} + 1.075\frac{V^2}{a}$$ Where: t_{RT} = perception-reaction time V = design speed, mi/h a = deceleration level, ft/s^2 (see discussion)



The following table presents driver PRTs and mean deceleration levels under favorable and unfavorable conditions calculated from driver responses to unexpected roadway hazards (*1*, *2*). The mean deceleration rates and 85th percentile values (3.7 m/s^2) are higher than those recommended in Lerner, Huey, McGee and Sullivan (*1*), but are shown to provide an indication of driver performance capabilities under emergency conditions.

Visibility	*Good Traction Conditions*			*Poor Traction Condition*		
	PRT	**Mean Deceleration Level (*a*)**		**PRT**	**Mean Deceleration Level (*a*)**	
		Metric	*US Customary*		*Metric*	*US Customary*
Good	1.6 s	5.4 m/s^2	17.7 ft/s^2	1.6 s	4.2 m/s^2	13.8 ft/s^2
Poor	5+ s	5.4 m/s^2	17.7 ft/s^2	5+ s	4.2 m/s^2	13.8 ft/s^2

Although the mean deceleration level differs for good (5.4 m/s^2) and poor (4.2 m/s^2) traction conditions, the 85th percentile values are the same (3.7 m/s^2).

Component	Favorable Conditions	Unfavorable Conditions
PRT	*Daytime* Hazard clearly visible and directly in driver's line of sight *Nighttime* Self-illuminated or retro-reflectorized hazard, with a lighting configuration that is immediately recognizable, near driver's line of sight	*Daytime* Hazard camouflaged by background and initially off line of sight *Nighttime* Hazard unreflectorized and not self-illuminated Lighting configuration is unfamiliar to the driver Low beams with or without street lighting Glare from oncoming vehicles
MT	Tangent with no grade Dry or wet pavement Passenger vehicles; tires in good condition Unexpected object	Curve Downgrade

Discussion

The PRT stage is significantly influenced by visibility conditions. In particular, the distance at which drivers can see an unilluminated, unreflectorized hazard depends on their headlights, their sensitivity to contrast, and their expectation of seeing the hazard. When drivers are not expecting a particular low-contrast hazard, their seeing distance is one half of that which would pertain if the object were expected. A very-low-contrast hazard may not even be detected in time to start braking. At speeds of 60 km/h and greater, using low-beam headlights, most drivers will be too close to an unexpected, unreflectorized hazard at the point they can detect it in time to stop (e.g., pedestrian in a dark coat). Also, the PRT component can be further increased by high workload (e.g., traffic merging, reading signs), fatigue, and impairment.

From an engineering perspective, the deceleration maneuver is significantly influenced by road surface conditions. From a human factors perspective, however, stopping is also influenced by the deceleration level that a driver adopts (which affects the braking efficiency). Under wet conditions, with standard brakes, the mean constant deceleration is about 0.43 *g* (54% of the pavement's coefficient of friction), and the 85th percentile is 0.38 *g* (47%). On wet pavements with anti-locking brake systems (ABSs), the mean constant deceleration is about 0.53 *g* (66% of the pavement's coefficient of friction), and the 85th percentile is about 0.45 *g* (56%). Under unfavorable conditions, slightly lower braking efficiencies (by 2% to 8%) are obtained on curves and tangents, but this information is based on physics because no human factors studies are available. Note also that downgrade MT can be increased by age and gender because older drivers and women will not apply as much braking force as younger drivers and males.

Some research suggests that under most rushed braking situations, drivers stop rapidly, but not to the point of locked wheel braking (in locked wheel braking, which is typical in crashes, drivers are 100% efficient in making use of the available pavement friction) (*2*). The mean maximum deceleration in one comprehensive study was about 75% of the pavement's coefficient of friction (*2*).

Design Issues

Stopping sight distance should always be provided because any road location can become a hazard. One study found that the most common objects hit on sight-restricted curves were large animals and parked cars (e.g., as provided by AASHTO (*3*)), the presence of which can create a hazard on any road section(*2*). If SSD is below standard at a number of locations then priorities must be set. Examples of hazards and conditions that may be high priority with respect to the need for SSD are:

- Change in lane width
- Reduction in lateral clearance
- Beginning of hazardous side slope
- Crest vertical curve
- Horizontal curve
- Driveway
- Narrow bridge
- Roadside hazards (e.g., boulder markers at driveways)
- Unmarked crossovers on high-speed rural arterials
- Unlit pedestrian crosswalks
- High-volume pedestrian crosswalks
- Frequent presence of parked vehicles very near or intruding into through lane

For design purposes, neither rapid nor locked wheel braking is a desirable driver response, because of the risk of skidding, or of a rear-end crash when there is a following vehicle. It should also be noted that the AASHTO model of driver deceleration assumes constant deceleration throughout the braking maneuver; however, empirical data suggest that maximum deceleration is generally not exhibited until the last part of the braking when the vehicle has slowed and come closer to the unexpected object (*2*). Under wet conditions, the 95th percentile value for equivalent constant deceleration without ABSs was 0.29 *g* (equivalent to 2.8 m/s^2 [9.3 ft/s^2]) and with ABSs, 0.41 *g* (equivalent to 4 m/s^2 [13.2 ft/s^2]).

Many design references use the term "design speed" to characterize the expected driving speed on a roadway. However, as noted in "Influence of Speed on Sight Distance" (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Key Components of Sight Distance, 5-2
Determining Intersection Sight Distance, 5-6
Determining When to Use Decision Sight Distance, 5-8

Key References

1. Lerner, N., Huey, R.W., McGee, H.W., and Sullivan, A. (1995). *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection. Volume I, Final Report* (FHWA-RD-93-168). Washington, DC: FHWA.
2. Fambro, D.B., Fitzpatrick, K., and Koppa, R.J. (1997). *NCHRP Report 400: Determination of Stopping Sight Distances*. Washington, DC: Transportation Research Board.
3. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.

DETERMINING INTERSECTION SIGHT DISTANCE

Introduction

Providing stopping sight distance at intersections is fundamental to intersection operation. In addition, drivers also require an unobstructed view of the entire intersection, including any traffic control devices, and sufficient lengths along the intersecting highway to permit the driver to anticipate and avoid potential collisions with other vehicles. Thus, *intersection sight distance* (ISD) differs depending on the type of intersection and maneuver involved. The different types of ISD are summarized in the table below.

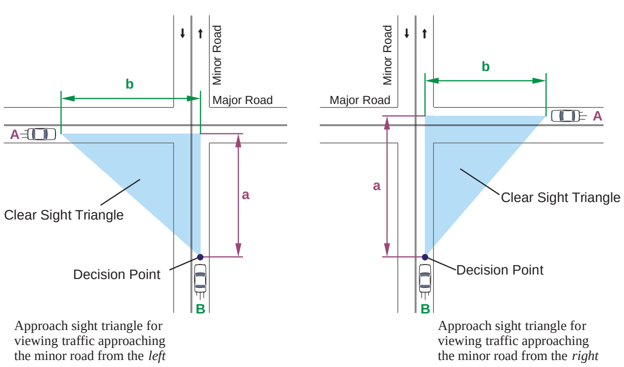
Design Guidelines

Case	Intersection Type and/or Maneuver	Sight Triangle	Sight Distance Determinant	Location in AASHTO (*1*)
A	Intersection with no control	Approach Triangle	Stopping sight distance with modified assumptions	Exhibit 9-51 Pg 655
B	Intersections with stop control on the minor road			
B1	Left turn from the minor road	Departure Triangle	Gap time equation	Exhibit 9-54 Pg 559
B2	Right turn from the minor road	Departure Triangle	Gap time equation	Exhibit 9-58 Pg 664
B3	Crossing maneuver from the minor road	Departure Triangle	Gap time equation	Exhibit 9-58 Pg 664
C	Intersections with yield control on the minor road			
C1	Crossing maneuver from the minor road	Approach Triangle	Stopping sight distance with modified assumptions	Exhibit 9-60 Pg 667
C2	Left turn from the minor road	Departure Triangle	Gap time equation	Exhibit 9-64 Pg 672
D	Intersections with traffic signal control	Both*	See Case D Guideline (*1*)	Pg 671
E	Intersections with all-way stop control	None	None required	Pg 674
F	Left turns from major road	Departure Triangle	Gap time equation	Exhibit 9-67 Pg 675

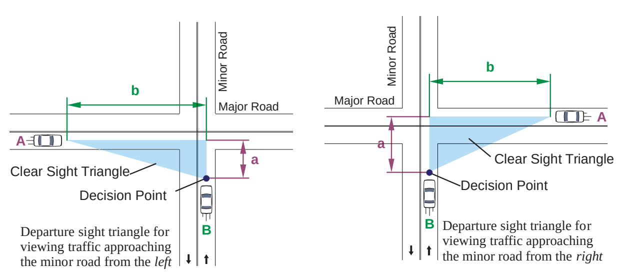
* First vehicle stopped on one approach should be visible to the driver of the first vehicle stopped on each of the other approaches and left-turning vehicles should have sufficient sight distance to select safe gaps in oncoming traffic.

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

The figure below shows the approach and departure triangles for different intersections/maneuvers.



Approach Triangles



Departure Triangles

Discussion

The two types of sight triangles used in calculating ISD are described below.

Approach Sight Triangles: According to AASHTO (*1*), "Each quadrant of an intersection should contain a triangular area free of obstructions that might block an *approaching* driver's view of potentially conflicting vehicles. The length of the legs of this triangular area [shown as "a" and "b" in the figure on the opposing page], along both intersecting roadways, should be such that the drivers can see any potentially conflicting vehicles in sufficient time to slow or stop before colliding within the intersection." The vertex of the triangle that is nearest to the approaching driver represents the decision point at which the driver must begin to stop if the driver determines that a potential conflict is possible.

Departure Sight Triangles: According to AASHTO (*1*), departure sight triangles provide "sight distance sufficient for a stopped driver on a minor-road approach to depart from the intersection and enter or cross the major road." In this case, the vertex of the sight triangle is positioned over the driver of the stationary departing vehicle and the length of the triangle represents how far ahead the driver must be able to check for oncoming traffic that would make the maneuver unsafe. According to AASHTO (*1*), the length of the triangle is based on an *acceptable gap time* (which is independent of oncoming vehicle speed) that provides the departing vehicle with sufficient time to safely accelerate, cross the intersection and thus complete the maneuver. The gap time varies based on the vehicle type (e.g., passenger vehicle, combination truck, etc.) and distance that the vehicle must cross during the maneuver (e.g., number of lanes).

Design Issues

Although desirable at higher volume intersections, approach sight triangles are not necessary at intersections controlled by two-way and all-way stop controls or traffic signals because the stopping requirement is determined by the controls and not by approaching vehicles.

Departure sight triangles should be provided in each quadrant of the intersection approach controlled by stop or yield signs and for some signalized intersections (see Case D (*1*)). Also grade adjustments are recommended if the departing vehicle's rear wheels are on an upgrade that exceeds 3% at the stop line (*1*).

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.

DETERMINING WHEN TO USE DECISION SIGHT DISTANCE

Introduction

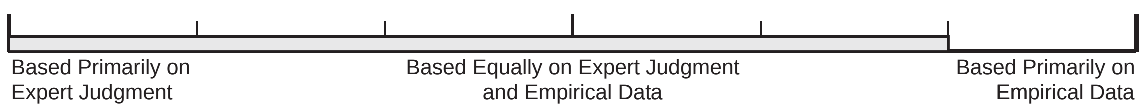
According to AASHTO (*1*, page 3-6), *decision sight distance* (DSD) represents a longer sight distance than is usually necessary for situations in which (1) drivers must make complex or instantaneous decisions, (2) information is difficult to perceive, or (3) unexpected or unusual maneuvers are required. DSD provides drivers with additional safety margin for error and affords them sufficient length to maneuver their vehicles at the same or reduced speed, rather than to just stop.

Design Guidelines

The following time values (t) and equations (from AASHTO (*1*)) should be used to calculate decision time in the following situations:

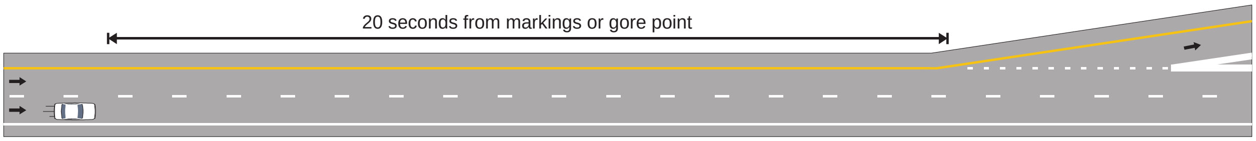
<table>
<tr><th>Avoidance Maneuver</th><th>A
Stop on Rural Road</th><th>B
Stop on Urban Road</th><th>C
Speed/Path/ Direction Change on Rural Road</th><th>D
Speed/Path/ Direction Change on Suburban Road</th><th>E
Speed/Path/ Direction Change on Urban Road</th></tr>
<tr><td>Time (t)</td><td>3.0 s</td><td>9.1 s</td><td>10.2–11.2 s</td><td>12.1–12.9 s</td><td>14.0–14.5 s</td></tr>
<tr><td rowspan="3">Equation</td><td>Metric</td><td>US Customary</td><td colspan="2">Metric</td><td>US Customary</td></tr>
<tr><td>$d = 0.278Vt + 0.039\frac{V^{t}}{a}$</td><td>$d = 1.47Vt + 1.075\frac{V^{t}}{a}$</td><td colspan="2">$d = 0.278Vt$</td><td>$d = 1.47Vt$</td></tr>
<tr><td>t = time (see above)
V = design speed (km/h)
a = driver decel. (m/s^2)</td><td>t = time (see above)
V = design speed (mi/h)
a = driver decel. (ft/s^2)</td><td colspan="2">t = time (see above)
V = design speed (km/h)</td><td>t = time (see above)
V = design speed (mi/h)</td></tr>
<tr><td>Common Examples</td><td colspan="2">- Guide signs, traffic signals
- Intersection where unusual or unexpected maneuvers are required
- The paved area of an intersection for (1) first intersection in a sequence or (2) isolated rural intersections</td><td colspan="3">- Lane markings indicating a change in cross section, overhead lane arrows
- A change in cross section (lane drop, two lanes to four lanes, four lanes to two lanes, passing lane, climbing lane, optional lane split, deceleration lane, channelized right turn lane)
- Lane closures in work zones</td></tr>
</table>

- Time value *t* represents the sum of the PRT and MT components.
- Deceleration values for Maneuvers A and B can be taken from SSD guideline (page 5-4).

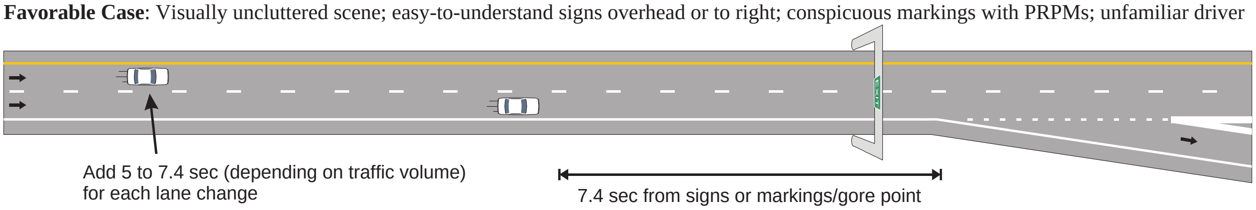


The figure below illustrates favorable and unfavorable conditions for Avoidance Maneuver E.

Unfavorable Case: Poor markings/signing, deceptive appearance of site, unexpected features (e.g., Freeway left exit);lane change required



Favorable Case: Visually uncluttered scene; easy-to-understand signs overhead or to right; conspicuous markings with PRPMs; unfamiliar driver



Discussion

Because some driving situations are particularly challenging (e.g., merging in moderate traffic during a lane drop), drivers require additional time to plan and execute the necessary maneuvers, or additional "safety margin" to compensate for errors they may make in the process. In these situations, use of DSD is appropriate because it incorporates the additional time that drivers need to complete more complicated driver actions. In particular, empirical data indicate that DSD is sufficiently long to accommodate the 85th percentile values in most challenging driving situations, even for older drivers. The DSD time specifically provides more time so that drivers can do the following:

1. Detect an unexpected or difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered (PRT)
2. Recognize the condition or its potential threat (PRT)
3. Select an appropriate speed and path (PRT)
4. Execute the appropriate maneuver safely and efficiently (MT)

In keeping with the components discussed in other sight distance guidelines (page 5-2), the first three of these tasks compose the PRT component while the fourth task is the MT component.

Although application of DSD is typically based on roadway features, certain situational factors can also adversely impact driver responsiveness. The frequent occurrence of the following factors at a site may indicate that the use of DSD is appropriate for that site:

- High driver workload due to concurrent tasks (e.g., traffic merging, reading signs)
- Truck traffic that intermittently blocks the view
- Off-roadway clutter that can distract drivers
- Poor weather that increases driver workload and makes cues (especially markings) less conspicuous
- High traffic volume levels

Design Issues

An important assumption when using DSD is that drivers are provided with and able to respond to signage that allows them to prepare in advance of the roadway feature. Studies indicate that when this advance information is not available or easy to miss, drivers may require additional time beyond the DSD. In these situations, driver responses are based on when they are able to see the actual roadway feature (e.g., turn arrow pavement marking, gore point), rather than on their perception of advance signage. In this situation, the 85th percentile maneuver completion time (including the PRT) is between 20 and 23 s from the point at which the feature becomes visible (*2*, *3*). Factors that may lead to these situations include the following:

- Dense traffic
- Poor marking and signing
- Deceptive appearance of site
- Features that violate driver expectancies (e.g., freeway left exit, add-drop lane)

Another design issue that warrants mention concerns lane changes. Additional sight distance may be necessary if drivers are expected to make multiple lane changes to complete a maneuver. In particular, each additional lane change adds an average of 5 s/lane in light traffic (≤ 725 vehicles/h) and 7.4 s/lane in medium-density traffic (726 to 1225 vehicles/h) to the maneuver.

Many design references use the term "design speed" to characterize the expected driving speed on a roadway. However, as noted in "Influence of Speed on Sight Distance" (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
2. Lerner, N., Huey, R.W., McGee, H.W., and Sullivan, A. (1995). *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection. Volume I, Final Report* (FHWA-RD-93-168). Washington, DC: FHWA.
3. McGee, H.W., Moore, W., Knapp, B.G., and Sanders, J.H. (1978). *Decision Sight Distance for Highway Design and Traffic Control Requirements* (FHWA-RD-78-78). Washington, DC: U.S. Department of Transportation.

DETERMINING PASSING SIGHT DISTANCE

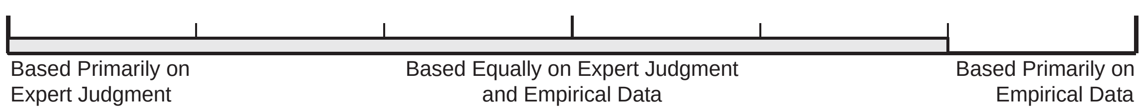
Introduction

According to AASHTO (*1*), *passing sight distance* (PSD) is how far ahead a driver must be able to see in order to complete a passing maneuver without cutting off the passed vehicle before meeting an opposing vehicle that appears during the maneuver. The guideline provides the design values for passes made at different speeds provided in AASHTO (*1*).

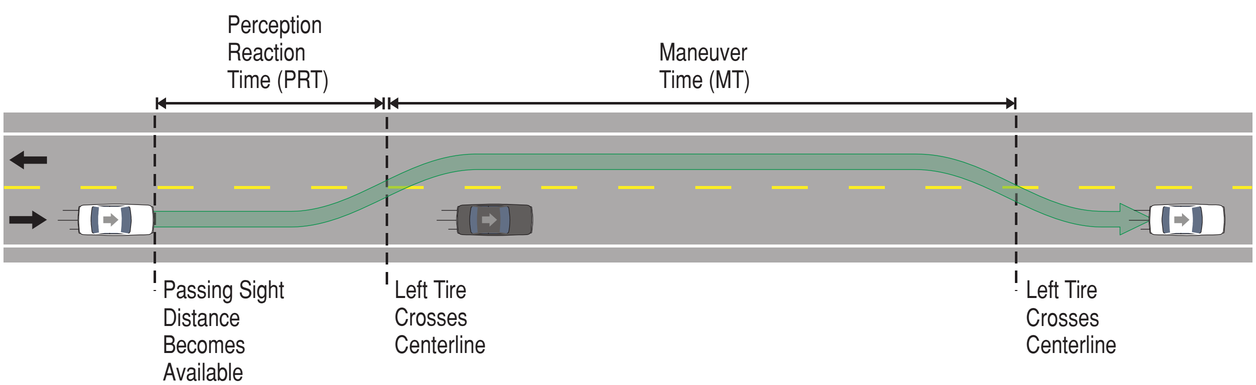
Design Guidelines

Metric				US Customary			
Design Speed (km/h)	Assumed Speeds (km/h) Passed Veh.	Assumed Speeds (km/h) Passing Veh.	Passing Sight Distance (m)	Design Speed (mi/h)	Assumed Speeds (mi/h) Passed Veh.	Assumed Speeds (mi/h) Passing Veh.	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

Note: The passing vehicle is assumed to be traveling 19 km/h or 12 mi/h faster than the passed vehicle.



The figure below shows the lane change maneuver used by the white car to pass the black car.



Discussion

The PSD encompasses both a PRT and an MT component. Mean PRTs to initiate a pass, measured from when PSD was available until when the **right** tire crossed the centerline, have been found to vary from 3.6 to 6.0 s, depending on the particular site on two-lane rural highways(*2*). No information is available on subject variability, but 85th percentile PRTs will certainly exceed mean reaction times. Just as other PRTs are affected by age, gender, standard transmissions, and day versus night conditions, PSD PRT may be as well; however, no studies were found on this issue. The primary cue that a driver uses to determine whether it is safe to initiate a pass is the size of the image of the oncoming vehicle. Research suggests that drivers make reasonable estimates of the distance of an oncoming car but not of its speed. This inability to reasonably estimate speed may be a more pronounced problem for older drivers.

MT is measured from the point at which either the left or right front tire (depending on study) of the subject vehicle crossed the centerline to the point at which the same front tire of the subject vehicle crossed the centerline back into the lane. One study found that on two-lane rural highways with approximately 96 km/h (60 mi/h) operating speeds and low traffic volumes (200 to 250 vehicles/h in the major direction and 85 to 175 vehicles/h in the minor direction), 65% to 75% of passes were attempted where there was no oncoming traffic, 25% to 35% of passes were attempted in the presence of oncoming traffic, and 0.8% of passes were aborted (*3*). In contrast, at high volumes (330 to 420 vehicles/h in the major direction and 70 to 170 vehicles/h in the minor direction), 51% to 76% of passes were made with no oncoming traffic, 26% to 50% of passes were in the presence of oncoming traffic, and 7.2 % of passes were aborted.

The average time in the opposing lane was 12.2 s under low traffic conditions and 11.3 s with high traffic volumes (based on when the front left tire—not the right tire as in the PRT case—entered and left the opposing lane). Depending on site and direction, times varied from a low of 8.0 s to a high of 12.9 s and there was no clear association between length of available passing lane and time spent in the opposing lane. At a speed of 96 km/h (60 mi/h) the average times in the opposing lane are equivalent to distances of 325 m (1064 ft) for low traffic and 301 m (986 ft) for high traffic.

Length of time spent in the passing lane is clearly related to the size of the time gap. In one study, drivers returning to their own lane with more than 10 s to spare averaged 12 s in the opposing lane. Drivers returning with 5 to 10 s to spare averaged 8.7 s and those with less than 5 s to spare, 6.8 s.

Drivers who pass may approach a slower vehicle and pass immediately (a flying pass), or may adopt a short headway and wait for an opportunity (a delayed pass). In the second case, more time for acceleration is required. In either case, drivers may adopt a short headway just prior to the pass. A study on two-lane highways found that 40% of drivers following at short headways (0.5 s or less) were doing so in anticipation of passing (*4*).

Design Issues

In passing situations, drivers' inaccurate estimates cannot be compensated for by increasing sight distance because the problem is that drivers misjudge the time they have to pass once they see the oncoming vehicle, and this problem remains the same regardless of how far down the road drivers can see. Instead, these types of crashes should be addressed through speed control measures or site factors that improve speed judgments.

Factors that increase the time needed to execute a passing maneuver include (1) a passenger vehicle passing multiple vehicles, (2) a passenger vehicle passing a truck, (3) a truck passing another vehicle, and (4) the passing occurring on an upgrade.

Many design references use the term "design speed" to characterize the expected driving speed on a roadway. However, as noted in "Influence of Speed on Sight Distance" (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Key Components of Sight Distance, 5-2

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.
2. Hostetter, R.S., and Seguin, E.L. (1969). The effects of sight distance and controlled impedance on passing behavior. *Highway Research Record, 299*, 64-78.
3. Kaub, A.R. (1990). Passing operations on a recreational two-lane, two-way highway. *Transportation Research Record, 1280*, 156-162.
4. Rajalin, S., Hassel, S.-O., and Summala, H. (1997). Close following drivers on two-lane highways. *Accident Analysis & Prevention, 29*(6), 723-729.

INFLUENCE OF SPEED ON SIGHT DISTANCE

Introduction

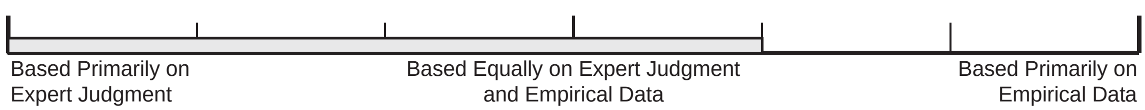
Although posted speed has been found to have the strongest association with operating speed, some visual aspects or driving-task demands associated with the roadway environment can "unconsciously" influence drivers' speed choice. Consequently, if operating speeds on a roadway significantly exceed design speed, sight distances on that roadway may be inadequate. In particular, drivers would have less time to react to an event or object at higher speed because they travel a greater distance during the initial PRT component of a response. Similarly, at higher speeds either vehicles take longer to stop/slow or maneuvers may become unsafe or overly difficult to perform.

Design Guidelines

If the operating speed of a roadway is substantially higher than the design speeds, increasing the sight distance to compensate for higher traveling speeds may be appropriate.

Examples of how design elements can cause operating speed to vary from design speed are shown in the table.

Design Element	Impact of Design on Speed
Lane Width	Increasing lane width from 3.3 to 3.8 m is associated with an increase of 2.85 km/h (1.78 mi/h) in speed on high design standard two-lane rural highways.
Alignment	Speed on curves can be reasonably accurately predicted using models based on radius, curve deflection angle, and curve length. Once the curve radius exceeds 800 m, curves have similar speeds to tangents. Speed on tangents is much more difficult to predict and depends on a wide array of road characteristics such as tangent length, radius of curve before and after the section, cross section, grade, general terrain, and sight distance. Posted speed is a better predictor of speed on urban arterial tangents than it is on highway tangents.
Pavement Surface	Some studies show pavement re-surfacing can be associated with a small (≈2 km/h) (1.25 mi/h) increase in speed.
Roadside Elements	Elements close to the edge of the lane (e.g., parked vehicles, foliage) contribute to a reduction in driver speed. Results of one study of road sections posted at 50 km/h (31 mi/h) showed that 85th percentile speeds were 12 km/h (7.5 mi/h) lower in road sections with side friction due to the presence of pedestrians, bicyclists, parked vehicles, etc.



The table below describes the relationship between operating speed and design element from past studies (*1*).

OPERATING SPEED RELATIONSHIP WITH DESIGN ELEMENT

Element	Direct	Inconclusive	None
Sight Distance	Stopping sight distance[1]	Decision sight distance; passing sight distance; intersection sight distance	
Horizontal Alignment	Radius	Superelevation	
Vertical Alignment	Grades; climbing lanes	Vertical curves	
Cross Section	Lane width[2]; curb and gutter[3]; lateral clearance	Cross slope	Shoulder width
Other	Radii/tangent length combos[3]; number of lanes[4], median type; access density		

[1]with limits; [2]weak; [3]per one study; [4]freeways;

Discussion

The design of a road affects drivers' speeds through two major mechanisms. First, the design creates the driving task. Narrow lanes and sharp curves make the driving task more difficult and lead to reductions in speed. Second, drivers have expectations about the posted speeds—and comfortable speeds—based on various combinations of design elements. Users of this guide should be aware that operating speeds may be very different from posted speed when the road message and the posted speed are at variance. Thus design sight distances may be more appropriately determined based on operating, not posted, speed. The effects of different design features on speed are discussed below:

Lane Width: Lane width influences speed because it influences the difficulty of the driving task. Narrower lanes require more frequent, smaller steering corrections, which correspond to more effort. Slowing down reduces the effort required.

Alignment: Speed is strongly related to radius of curvature. Typically, models of predicted speed based on radius, deflection angle, and curve length account for more than 80% of the variance in speed. Similarly, one study of speeds in 176 curves on rural two-lane highways with posted speeds of 75 to 115 km/h found that V85 was most strongly related to radius and related, but less so, to grade and sight distance (R values .58 to .92) (*2*). Once the curve radius exceeded 800 m, curves had similar speeds to tangents. Speed on tangents is much more difficult to predict and is dependent on a wide array of road characteristics such as tangent length, radius of curve before and after the section, cross section, grade, general terrain, and sight distance. Accordingly, studies on urban arterials find posted speed limits typically account for only half of the variance in speed.

Pavement Surface: One of the cues drivers use to estimate their own speed is noise level. When sound cues were removed through the use of earmuffs, drivers underestimated their actual speeds by 6 to 10 km/h (*3*). Also, some studies suggest re-surfacing a road can result in a speed increase of 2 km/h.

Roadside Elements: Elements close to the edge of the lane—such as pedestrians, bicyclists, parked vehicles, and foliage—can strongly affect speed. One of the major cues used by drivers is the streaming of information in peripheral vision. Side friction increases the stimulus in peripheral vision, giving a sense of higher speed or greater hazard. In one study, drivers were asked to drive at 60 mi/h (96 km/h) with the speedometer covered. In an open-road situation, drivers averaged 57 mi/h (91 km/h). However, along a tree-lined route, drivers averaged 53 mi/h (85 km/h) (*4*). The trees, close by, provided peripheral stimulation, giving a sense of higher speed or greater hazard. The elements that create side friction—such as pedestrians, bicyclists, parked vehicles, and landscaping—also present various levels of hazard, likely influencing drivers to slow down to various degrees. In other words, pedestrian presence close to the road edge is more likely to affect speed than landscaping close to the road edge.

Design Issues

The relationship between several design elements and operating speed was investigated in a previous review of design elements (*1*). In some cases the relationship was found to be strong, such as for horizontal curves; however, for several other cases, such as lane width, the relationship was found to be weak. In all cases when a relationship between the design element and operation speed exists, there are ranges when the influence of the design element on speed is minimal.

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4
Determining Passing Sight Distance, 5-10

Key References

1. Fitzpatrick, K., Carlson, P.J., Brewer, M.A., Wooldridge, M.D., and Miaou, S.-P. (2003). *NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices.* Washington DC: Transportation Research Board.
2. Fitzpatrick, K., Carlson, P.J., Wooldridge, M.D., and Brewer, M.A. (2000). *Design Factors that Affect Driver Speed on Suburban Arterials* (FHWA/TX-001/1769-3). Washington, DC: FHWA.
3. Evans, L. (1970). Speed estimation from a moving automobile. *Ergonomics 13*, 219-230.
4. Shinar, D., McDowell, E., and Rockwell, T.H. (1977). Eye movements in curve negotiation. *Human Factors, 19(1),* 63-71.

KEY REFERENCES FOR SIGHT DISTANCE INFORMATION

Introduction

Sight distance requirements, issues, and subtopics have been covered extensively in a range of standard reference sources for roadway design and highway. It is important for roadway designers and traffic engineers to recognize that most of the information presented in this chapter has been adopted from these other sources and for users of this HFG to know where to go to find alternative sources of sight distance information.

Design Guidelines

The list below summarizes source and chapter for sight distance information from key reference sources:

***A Policy on Geometric Design of Highways and Streets* (2011)**

- Chapter 2, Design Controls and Criteria, discusses driver reaction time and related issues in Driver Performance and Human Factors subhead.
- Chapter 3, Elements of Design, has a section on sight distance, with subsections on stopping sight distance, decision sight distance, passing sight distance for two-lane highways, and sight distance for multilane highways.
- Chapters 5 (Local Roads and Streets), 6 (Collector Roads and Streets), 7 (Rural and Urban Arterials), and 9 (Intersections) all have a number of specific subsections on sight distance.

***Manual on Uniform Traffic Control Devices (MUTCD)* (2009)**

- The MUTCD has several figures and tables relating minimum sight distance to speed. These include Table 3B-1 (for passing sight distance), Table 4D-2 (for traffic control signal sight distance), Table 6C-2 (for work zone longitudinal buffer space), and Table 6E-1 (for work zone flagger stations).
- Section 2C.05, Placement of Warning Signs, describes a PRT model. Table 2C-4 (English units) shows advance warning sign placement as a function of speed based on PRT requirements.

***ITE Traffic Engineering Handbook* (1999)**

- Chapter 2, Road Users, has sections on PRT and sight distance.
- Chapter 11, Geometric Design of Highways, has a section on sight distance, with subsections on stopping sight distance, passing sight distance, decision sight distance, and intersection sight distance.

***ITE Traffic Control Devices Handbook* (2001)**

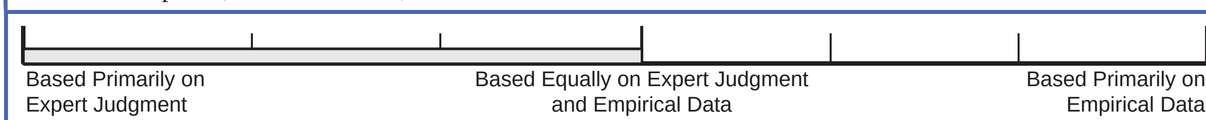
- Chapter 2, Human Factors, has sections on driver PRT and maneuver time.
- Chapter 11, Highway-Rail Grade Crossings, contains discussion of sight distance requirements for at-grade crossings.

***Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians* (2001)**

- Sections on Intersections (I) and Roadway Curvature and Passing Zones (III) contain discussions of sight distance.

***Highway Safety Manual* (2010)**

- Chapter 2, Human Factors, has sections on PRT and factors that affect its duration.



Discussion

The HFG focuses on key aspects of sight distance from the roadway users' perspective and is not intended to provide a comprehensive or definitive presentation of sight distance. Additional data sources follow:

A Policy on Geometric Design of Highways and Streets (*1*) provides guidance to roadway designers in the form of recommended values for a host of critical design dimensions. It is based on both established practices and standards, and reflects recent research. Most of the chapters contain sections or subsections that focus on user needs and characteristics; as noted above, Chapters 2, 3, 5, 6, 7, and 9 contain sight distance information.

The *Manual on Uniform Traffic Control Devices* (*2*) is the national standard for traffic control devices installed on any street, highway, or bicycle trail open to public travel. MUTCD provides uniform standards for the design of all signs, signals, markings, and other devices that are used to regulate, warn, or guide traffic and that are placed on, over, or adjacent to streets, highways, pedestrian facilities, and bikeways. Though MUTCD does not address sight distance issues as comprehensively as *A Policy on Geometric Design of Highways and Streets*, it does provide a number of very accessible and useful figures and tables on sight distance.

The *Traffic Engineering Handbook* (*3*) provides relevant key principles and techniques on "best" traffic engineering practices.

The *Traffic Control Devices Handbook* (*4*) is intended to augment and supplement the MUTCD by providing additional information and background information on selected topics. Although sight distance is not addressed as a separate chapter, PRT and MT are addressed in Chapter 2, Human Factors, and sight distance requirements for at-grade crossings are covered in Chapter 11, Highway-Rail Grade Crossings.

Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians (*5*) focuses on older roadway users but includes relevant information from key sources relating to sight distance (see also the accompanying handbook for these guidelines, published as FHWA-RD-01-103).

The *Highway Safety Manual* (*6*) has limited information about estimating sight distance; however, it includes some discussion of sight distance as a contributing factor in crashes.

Design Issues

None

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4
Determining Intersection Sight Distance, 5-6
Determining When to Use Decision Sight Distance, 5-8
Determining Passing Sight Distance, 5-10
Influence of Speed on Sight Distance, 5-12

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
2. FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
3. Pline, J.L. (Ed.). (1999). *Traffic Engineering Handbook, Fifth Edition*. Washington, DC: ITE.
4. Pline, J.L. (Ed.). (2001). *Traffic Control Devices Handbook*. Washington, DC: ITE.
5. Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001) *Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians* (FHWA-RD-01-051). McLean, VA: FHWA, Research, Office of Safety R&D.
6. AASHTO (2010). *Highway Safety Manual, 1st Edition*. Washington, DC.

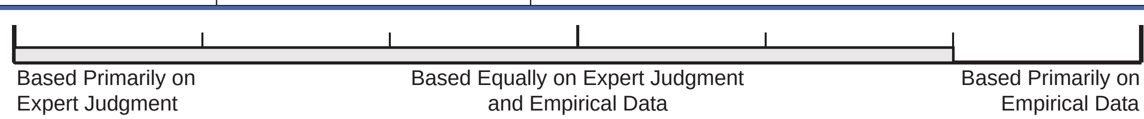
WHERE TO FIND SIGHT DISTANCE INFORMATION FOR SPECIFIC ROADWAY FEATURES

Introduction

The following table lists the information required to diagnose sight distance for specific roadway features. Although the roadway designer and the traffic engineer work with distances, sight distance needs actually originate from driver MT needs and speed choice. Therefore, to understand, diagnose, and address sight distance concerns, one must address the human factors issues of time and speed. Stopping sight distance is needed for all roadway features.

Design Guidelines

Feature or Problem	Type of Sight Distance Requirement	Information Required	Location of Information
All Roadway Features	Stopping sight distance	Operating speed	→ Determine
		Sight distance to hazard	→ Determine
		Required SSD	→ AASHTO, Table 3-1 (*1*)
Horizontal Curve	Stopping sight distance	Operating speed	→ Determine
		Sight distance to hazard	→ Determine
		Required SSD	→ AASHTO, Table 3-2 (*1*)
Horizontal Curve Approach with Warning Sign	Maneuver sight distance	Curve recommended speed	→ Determine
		Speed on approach	→ Determine
		Sign location	→ Determine
		Sign placement guidelines	→ MUTCD, Table 2C-4 (*2*)
Vertical Curve	Stopping sight distance	Operating speed	→ Determine
		Rate of vertical curvature, K	→ AASHTO, Table 3-34 (*1*)
Vertical Curve	Passing sight distance	Operating speed	→ Determine
		Rate of vertical curvature, K	→ AASHTO, Table 3-35 (*1*)
Warning Sign	Maneuver sight distance	Warning sign placement guidelines	→ MUTCD, Table 2C-4 (*2*)
Guide Sign	Maneuver sight distance	Typical placement of route signs	→ MUTCD, Figure 2D-6 (*2*)
Signed Lane Drop	Decision sight distance	Operating speed	→ Determine
		Avoidance maneuver C, D, or E	→ Determine
		DSD	→ AASHTO, Table 3-3 (*1*)



Discussion

The sight distance diagnostic procedure consists of a systematic on-site investigation technique to evaluate the highway environment to support sight distance needs. The highway location is surveyed, diagrammed, and divided into component sections based on specific driving demands (e.g., need to perform a specific maneuver). Then each section is analyzed in terms of its suitability to support the required task (e.g., information provided to the driver, allotted time to complete the required task or maneuver). This procedure enables the practitioner to compare the available sight distance with the sight distance required to perform the driving task safely.

Procedures for measuring available sight distance are given in AASHTO (*1*) and the *Manual of Transportation Engineering Studies* (*3*). Available sight distance can be checked on plans for proposed designs or in the field for existing locations.

Design Issues

Many design references use the term “design speed” to characterize the expected driving speed on a roadway. However, as noted in “Influence of Speed on Sight Distance” (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Tutorial 1: Real-World Driver Behavior Versus Design Models, 22-2
Tutorial 2: Diagnosing Sight Distance Problems and Other Design Deficiencies, 22-9

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.
2. FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
3. Robertson, H.D., Hummer, J.E., and Nelson, D.C.(Eds.) (2000). *Manual of Transportation Engineering Studies*. Washington, DC: ITE.

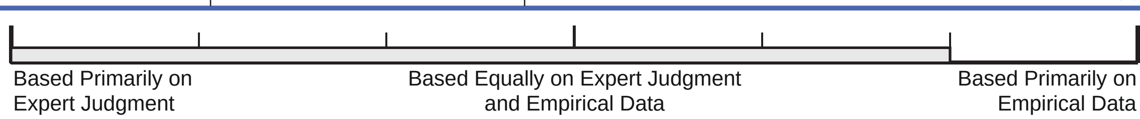
WHERE TO FIND SIGHT DISTANCE INFORMATION FOR INTERSECTIONS

Introduction

The following table lists the information required to diagnose sight distance at various intersection types. Although the roadway designer and the traffic engineer work with distances, sight distance needs actually originate from driver MT needs and speed choice. Therefore, to understand, diagnose, and address sight distance concerns, one must address the human factors issues of time and speed. Stopping sight distance is needed for all roadway features.

Design Guidelines

Feature or Problem	Type of Sight Distance Requirement	Information Required	Location of Information
Uncontrolled Intersection	Intersection sight distance	Sight triangle	→ Determine
		Operating speed	→ Determine
		Length of sight triangle legs	→ AASHTO, Table 9-3 (*1*)
Two-Way Stop Intersection	Intersection sight distance	Operating Speed	→ Determine
	Case B1	ISD-Case B1	→ AASHTO, Table 9-6 (*1*)
	Case B2	ISD-Case B2	→ AASHTO, Table 9-8 (*1*)
	Case B3	ISD-Case B3	→ AASHTO, Table 9-8 (*1*)
Intersection with Yield Control on Minor Road	Intersection sight distance	Operating Speed	→ Determine
	Case C1	ISD-Case C1	→ AASHTO, Tables 9-9 & 9-10 (*1*)
	Case C2	ISD-Case C2	→ AASHTO, Table 9-12 (*1*)
Left turns from Major Road	Intersection sight distance—Case F	Time gap	→ AASHTO, Table 9-13 (*1*)
		Operating speed	→ Determine
		ISD-Case F	→ AASHTO, Table 9-14 (*1*)
Four-Way Stop Intersection	Intersection sight distance—Case E	None required	→ None required for ISD
Signalized Intersection	Intersection sight distance—Case D	None required for basic	→ None required for ISD signal operation
Roundabout	Stopping sight distance	Operating speed	→ Determine
		Required SSD	→ AASHTO, Table 3-1 (*1*)
	Intersection sight distance	Sight triangle	→ Determine
		Length of conflicting leg	→ Roundabout Guide, Exhibit 6-33 (*2*)
Railroad-Highway Grade Crossing	RHGC sight distance sight triangle	Speed of vehicle	→ Determine
		Speed of train	→ Determine
	Case A	Distance from rail to stop line	→ Determine
	Case B	Required RHGC sight distance	→ AASHTO, Table 9-32 (*1*)
Approach to Stop Condition	Decision sight distance	Operating speed	→ Determine
		Avoidance maneuver A or B	→ Determine
		DSD	→ AASHTO, Table 3-3 (*1*)



Discussion

The sight distance diagnostic procedure consists of a systematic on-site investigation technique to evaluate the highway environment to support sight distance needs. The highway location is surveyed, diagrammed, and divided into component sections based on specific driving demands (e.g., need to perform a specific maneuver). Then each section is analyzed in terms of its suitability to support the required task (e.g., information provided to the driver, allotted time to complete the required task or maneuver). This procedure enables the practitioner to compare the available sight distance with the sight distance required to perform the driving task safely.

Procedures for measuring available sight distance are given in AASHTO (*1*) and Robertson, Hummer, and Nelson, (*4*). Available sight distance can be checked on plans for proposed designs or in the field for existing locations. Tustin, Richards, McGee, and Patterson (*3*) and Robertson et al. (*4*) provide additional information that may be useful for determining sight distance.

Design Issues

Many design references use the term “design speed” to characterize the expected driving speed on a roadway. However, as noted in “Influence of Speed on Sight Distance” (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Tutorial 1: Real-World Driver Behavior Versus Design Models, 22-2
Tutorial 2: Diagnosing Sight Distance Problems and Other Design Deficiencies, 22-9

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.
2. FHWA (2000). *Roundabouts: An Informational Guide* (Publication FHWA-RD-00-067). Washington, DC.
3. Tustin, B., Richards, H., McGee, H., and Patterson, R. (1986). *Railroad-Highway Grade Crossing Handbook, Second Edition* (FHWA-TS-86-215). Fairfax, VA: Tustin Enterprises.
4. Robertson, H.D., Hummer, J.E., and Nelson, D.C. (2000). *Manual of Transportation Engineering Studies*. Washington, DC: ITE.

CHAPTER 6

Curves (Horizontal Alignment)

TASK ANALYSIS OF CURVE DRIVING

Introduction

This guideline identifies the basic activities that drivers would typically perform while trying to safely navigate a single horizontal curve. This information is useful because (1) it can help identify segments of the curve driving task that are more demanding and require the driver to pay closer attention to basic vehicle control and visual information acquisition, and (2) it identifies the key information and vehicle control requirements in different parts of the curve driving task. This information has design implications because workload is influenced by design aspects such as design consistency, degree of curvature, and lane width. In particular, identifying high workload components of the curve driving task provides an indication of where drivers could benefit from having their driving tasks made easier to perform (e.g., clearer roadway delineation, wider lanes, longer radius), or benefit from the elimination of potential visual distractions.

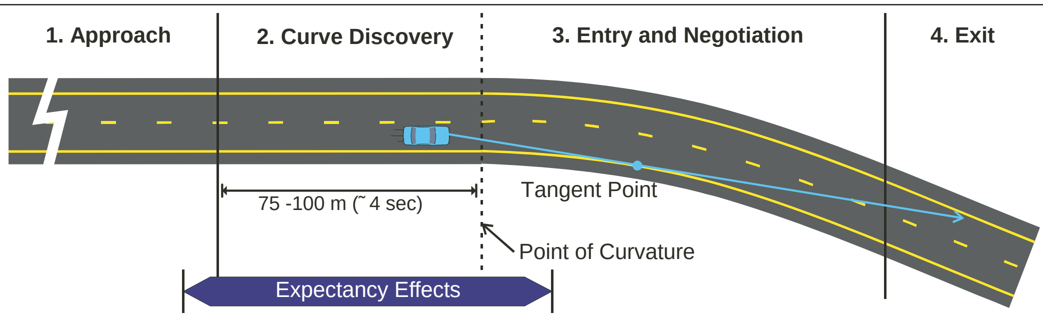
Design Guidelines

Because drivers have higher visual demands during curve entry and navigation—especially with sharp curves—curves should be designed to minimize additional workload imposed on drivers. Driver visual demands are greatest just before and during curve entry and navigation because drivers typically spend most of their time looking at the immediate roadway for vehicle guidance information.

Some General Implications for the Design of Horizontal Curves

- Avoid presenting visually complex information (e.g., that requires reading and/or interpretation) within 75 to 100 m or 4 to 5 s of the point of curvature, or within it.
- Key navigation and guidance information, such as lane markings and delineators/reflectors, should be clearly visible in peripheral vision, especially under nighttime conditions.
- Minimize the presence of nearby visual stimuli that are potentially distracting (e.g., signage/advertisements that “pop out” or irregular/unusual roadside scenery/foliage).
- Visual demands appear to be linearly related to curve radius and unrelated to deflection angle. Curves with a curvature of 9 degrees or greater are highly demanding relative to more gradual curves.

The figure and table below show the different curve segments, as well as key driving tasks and constraints.



	1. Approach	2. Curve Discovery	3. Entry and Negotiation	4. Exit
Key Driving Tasks	1.1 Locate bend 1.2 Get available speed information from signage 1.3 Make initial speed adjustments	2.1 Determine curvature 2.2 Assess roadway conditions 2.3 Make additional speed adjustments 2.4 Adjust path for curve entry	3.1 Adjust speed based on curvature/lateral acceleration 3.2 Maintain proper trajectory 3.3 Maintain safe lane position	4.1 Accelerate to appropriate speed 4.2 Adjust lane position
Visual Demands & Info Sources	**Low/Flexible** • Primarily environment driven	**Med. Increasing to High** • Curvature perception cues • Observing roadway conditions	**High** • Most fixations to tangent point	**Low** • Vehicle position information
Effective Info Modes	• Advisory/message signs	• Non-verbal (e.g., chevrons) and direct info (e.g., delineators)	• Direct info only (lane markings; raised markers)	• No constraints
Vehicle-Control Demands	• None	• Anticipatory positioning • Curve cutting	• Continuous heading adjustments	• Lane position adjustments
Primary Speed Influences	• Previous roadway elements & signage	• Expectations & curvature cues	• Expectations & lateral acceleration	• Posted speed or expectations

Discussion

The information about driving tasks in the previous page is taken from the task analysis described in Tutorial 3 that breaks down curve driving into its perceptual, cognitive, and psychomotor components. A key concept for understanding the curve driving task is the visual and vehicle-control demand, which refers to the amount of time that drivers are required to focus their attention on curve driving activities, such as acquisition of visual information and maintaining vehicle control, to the exclusion of other activities they could otherwise be doing while driving (e.g., scanning for hazards, viewing scenery, changing the radio station, etc.).

Visual demands: During the Approach segment, the time and effort that drivers typically spend acquiring information needed to safely navigate a curve is low and driven primarily by the driving environment (e.g., other vehicles, scenery). During Curve Discovery, visual demands increase to high levels at the point of curvature, as drivers scan the curve for information that they need to judge the degree of curvature. Visual demands are highest just after the point of curvature (Entry and Negotiation segment) and drivers spend most of their time looking at the tangent point to keep their vehicle aligned with the roadway (*1*, *2*, *3*). For more gradual curves (e.g., 3 degrees), drivers spend more time looking toward the forward horizon than the tangent point (*3*).

Vehicle-control demands: The driver workload imposed by the need to keep the vehicle safely within the lane is minimal up through the end of the Curve Discovery segment, at which point many drivers will adjust their lane position to facilitate curve cutting. Demands are highest during the Entry and Negotiation segment as drivers must continuously adjust the vehicle trajectory to stay within the lane. Moreover, these demands are higher for curves with a shorter radii and smaller lane width (*1*). During the Exit segment, drivers may adjust their lane position with minimal time pressure, unless there is another curve ahead.

Effective information modes: The type of curve-related sign/delineator information that is most likely to be useful to drivers differs in each curve segment. During the Approach, drivers have fewer visual demands and have more time available to read more complex signs, such as speed advisory signs. During the Curve Discovery segment, conspicuous non-verbal information, such as chevrons, are more effective because drivers spend more time examining the curve and have less time available to read, comprehend, and act on text-based information. During Entry and Negotiation, drivers spend most of their time looking at the tangent point, and only direct information presented where they are looking (e.g., lane markings) or information that can be seen using peripheral vision (e.g., raised reflective marking at night) should be relied upon to communicate curve information.

Speed selection: Driver expectancy and speed-advisory sign information form the primary basis for speed selection; however, the effectiveness of advisory information may be undermined by expectancy and roadway cues (*4*). Curve perception also plays an important role in speed selection and inappropriate curvature judgments (e.g., in horizontal curves with vertical sag). Once drivers are in the curve, lateral acceleration felt by drivers and likely vehicle handling workload provide the primary cues for adjusting speed.

Expectancy effects: Driver expectations about a curve and, more broadly, design consistency are important factors in drivers' judgments about curvature and corresponding speed selection during the Curve Discovery segment (*1*). While direct cues, such as lane width and the visual image of the curve, influence speed selection, expectations based on previous experience with the curve and roadway (e.g., previous tangent length) also significantly influence speed selection (*4*). Mitigations to recalibrate driver expectancies (e.g., via signage) would likely be most effective prior to the Curve Discovery segment.

Design Issues

Visual demands appear to be related linearly and inversely to curve radius, but not to deflection angle. Curves sharper than 9 degrees are significantly more demanding than shallower curves or tangents, however, there is no clear, unambiguous threshold regarding what constitutes a sharp curve based on workload data (*1*, *2*). Also, curve direction does not seem to affect workload (*2*).

Additionally, it is unclear whether the 75 to 100 m length of the Curve Discovery segment is based on distance or time. The primary studies that investigated visual demand used the same fixed 45 mi/h travel speed, so it is currently unknown whether the 75 to 100 m fore-distance applies with other speeds (*1*, *2*).

Cross References

The Influence of Perceptual Factors on Curve Driving, 6-4
Speed Selection on Horizontal Curves, 6-6
Countermeasures for Improving Steering and Vehicle Control Through Curves, 6-8
Countermeasures to Improve Pavement Delineation, 6-10
Signs on Horizontal Curves, 6-12

Key References

1. Krammes, R. A., Brackett, R. Q., Shafer, M. A., Ottesen, J. L., Anderson, I. B., Fink, K. L., Collins, K. M., Pendleton, O.J., and Messer, C.J. (1995). *Horizontal Alignment Design Consistency for Rural Two-Lane Highways.* Final Report. (Report FHWA-RD-94-034). McLean, VA: FHWA.
2. Fitzpatrick, K., Wooldridge, M. D., Tsimhoni, O., Collins, J. M., Green, P., Bauer, K. M., Parma, K. D., Koppa, R., Harwood, D. W. Anderson, I., Krammes, R. A., and Poggioli, B. (2000). *Alternative Design Consistency Rating Methods for Two-Lane Rural Highways.* Final Report. (Report FHWA-RD-99-172). McLean, VA: FHWA.
3. Serafin, C. (1994). *Driver Eye Fixations on Rural Roads: Insight into Safe Driving Behavior.* Interim Report. (Report No. UMTRI-94-21). Ann Arbor: University of Michigan Transportation Research Institute.
4. Fitzpatrick, K., Carlson, P., Brewer, M. A., Wooldridge, M. D., and Miaou, S.-P. (2003). *NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices.* Washington, DC: Transportation Research Board.

THE INFLUENCE OF PERCEPTUAL FACTORS ON CURVE DRIVING

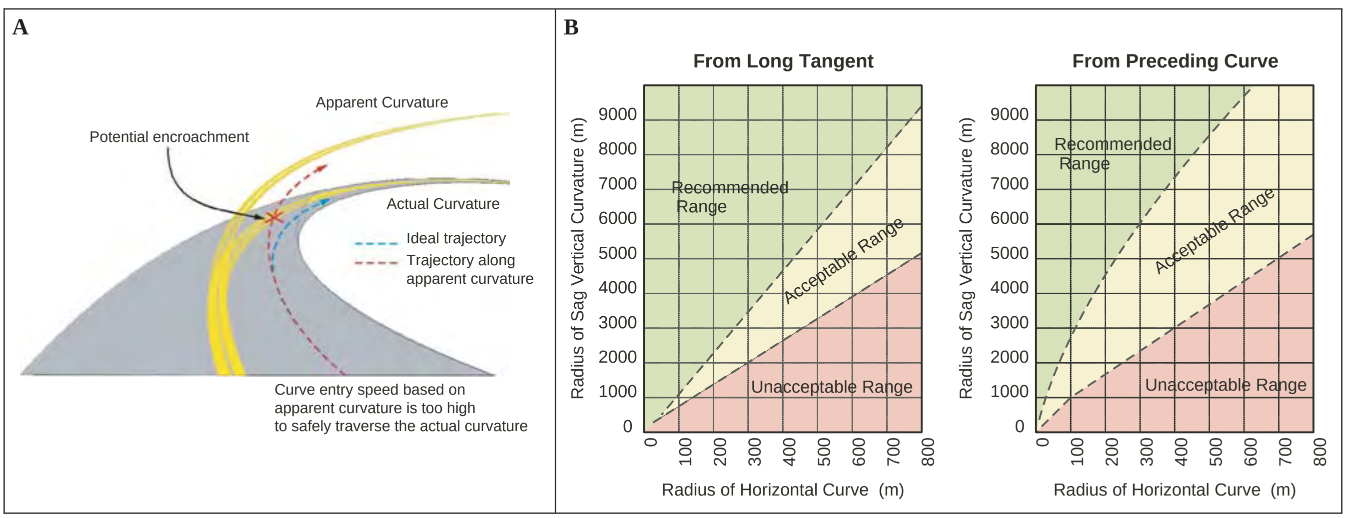
Introduction

The perceptual factors in curve driving refer to the driver's use of visual information to assess the curvature of an upcoming curve. This activity is important because a driver's perception of an upcoming curve's radius forms the primary basis for making speed and path adjustments prior to curve entry. The curve radius as seen from the driver's perspective is called the *apparent radius*. Although drivers will use speed information from signs, in practice, driver speed selection in curves is heavily influenced by roadway features (*1*), and the apparent radius appears be the primary determining factor of speed at curve entry (*2*). The primary design challenge regarding curve perception is that the apparent radius can appear distorted—either flatter or sharper—depending on the topography and other road elements. Of particular concern are combination curves that include a vertical sag superimposed on a horizontal curve. From the driver's perspective, this combination makes the horizontal curve appear flatter than it actually is (See A in the figure below). Consequently, drivers may be inclined to adopt a curve entry speed that is faster than appropriate based on horizontal curvature alone.

Design Guidelines

Sag horizontal curves that have a visual appearance (apparent horizontal radius) that is substantially different from the plan radius should be given careful consideration because they may lead to curve entry speeds that are faster than expected based on horizontal curvature alone.

Based Primarily on Expert Judgment	Based Equally on Expert Judgment and Empirical Data	Based Primarily on Empirical Data



A. A vertical sag curve produces a visual image (shaded roadway) that a driver would perceive as having an apparent radius that is larger than the actual radius.

B. Nomographs indicating vertical and horizontal curve radius combinations that result in apparent radii that may result in curve entry speeds that are unintentionally faster than expected based on horizontal curvature alone (red shaded region), and which possibly represent a safety risk (*2*).

Note that the nomographs present vertical curvature in terms of radius (in meters) and not *K*, which is the typical approach for representing vertical curvature. The reason for presenting curvature as a radius is that the geometric calculations for computing visual distortion rely on circular arcs. The nomographs can be used to provide a "rule of thumb" check for potentially problematic curve combinations assuming the vertical curvature component can be generally approximated by a circle with an arc intersecting the low point of Type III curves and vertical points of curvature on both sides.

Discussion

Curve perception is an important part of curve driving because, in the absence of extensive experience with a curve, drivers must rely on their judgments about a curve to select a safe speed for curve entry. Speed signage information can assist drivers; however, evidence suggests that this information is not a primary source for speed selection in curves (*1*). Therefore, driver expectations (influenced by design consistency) and the visual information the driver obtains about the curve are the primary basis for speed selection.

Sag horizontal curves can cause drivers to significantly underestimate the sharpness of a curve because of a visual distortion from the driver's viewing perspective; i.e., the apparent radius appears to be longer than the plan radius. Thus, these sag horizontal curves, are also associated with higher entry speeds and crash rates (*2*, *3*).

The optical aspects of this phenomenon have been derived analytically, and the results were used to make the nomographs presented on the previous page. Horizontal and vertical curve radius combinations that fall in the unacceptable range are associated with significant visual distortion, and also associated with higher than 85th percentile speeds and higher crash rates (*2*). Note that this validation is based on European data, and these findings have not been investigated on US roads. However, the optical properties of this phenomenon are universal and should be equally applicable to all drivers (*4*). This analytical work also assumes a 75 m viewing distance, which is comparable to the start of the Curve Discovery segment of curve driving, in which drivers spend most of their time inspecting the curve. Distortion effects may be reduced somewhat at further viewing distances; however, assuming a 75 m viewing distance is consistent with driver behavior and is more conservative.

Visual distortion also occurs when crest vertical curves are superimposed on horizontal curves; such curves appear sharper than the plan radius. This typically results in slower 85th percentile entry speeds (*2*, *3*). However, a crest horizontal curve with a vertical curvature that approximates a circular radius of *less than 3 times* the horizontal curve radius could present a discontinuous visual image of the curve (e.g., the part of the roadway just behind the crest is occluded) (*2*). Such a crest horizontal curve is potentially inconsistent with driver expectations and could compromise roadway safety by causing drivers to suddenly brake hard if they are surprised by the curve appearance. However, there are currently no empirical data showing that this is an actual safety issue.

Design Issues

A summary of the relevant research findings regarding curve perception in general and the corresponding degree of empirical support is shown in the table below. While no specific values or recommendations can be made for these aspects, it is useful to take them into consideration during curve design, especially if other aspects of the curve design suggest that there may be a potential problem with driver perception of the curve radius.

Aspect	Effect	Empirical Support
Superimposed Vertical Sag	Makes a curve appear flatter	Strong
Cross Slope	For sag horizontal curves, the greater the cross slope and lane width, the greater the apparent flattening of the horizontal curve	Analytical evidence
Superimposed Vertical Crest	Makes a curve appear sharper and may cause discontinuities in curve	Strong
Deflection Angle	Holding radius constant, greater deflection angle makes the curve appear sharper, especially for smaller radii	Moderate
Delineators	Delineators provide drivers with more information to judge the curve radius, which improves accuracy of these judgments	Moderate
Spiral	May make curve appear flatter, or make curve perception more difficult, because the onset of the curve is less apparent	Indirect
Signage	Drivers perceive curve as "riskier" if signs indicate that the curve is hazardous	Suggestive

Cross References

Task Analysis of Curve Driving, 6-2

Key References

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SPEED SELECTION ON HORIZONTAL CURVES

Introduction

Various sources attempt to examine speed data for roadway geometry and to determine desirable speeds for horizontal curves. AASHTO policy defines design speed as “a selected speed used to determine the various geometric design features of the roadway” (*1*).

The design speeds on horizontal curves should be set at a value determined by AASHTO policy and factors determined from a survey of state DOTs. AASHTO policy (*1*) considers factors such as functional classification, rural vs. urban environment, and terrain type; state DOTs typically consider factors such as functional classification, legal speed limit (as well as legal speed limit plus an adjustment value of 5 or 10 mi/h), anticipated volume, terrain type, development, costs, and design consistency.

Design Guidelines

A number of vehicle, driver, and roadway variables should be considered when determining speed limits for horizontal curves. A procedure to calculate appropriate speeds has been adapted from Charlton and de Pont (*2*) and is outlined below. If these factors are common at an intersection location, then consideration should be given to modifying the gap acceptance design assumptions.

Step	Procedures for Determining Curve Advisory Speed Limits
1	Determine curve radius (*R*), superelevation, and offset distance from center of lane to any visual obstruction (*O*).
2	Determine the vehicle’s maximum possible lateral acceleration and braking coefficient. The maximum lateral acceleration is limited by rollover stability for most heavy vehicles and by tire adhesion for passenger cars. Typical values to use for dry conditions are 0.35 *g* for laden heavy vehicles, 0.7 *g* for buses and SUVs, and 0.8 *g* for passenger cars. The braking coefficient reflects the maximum braking efficiency that can be achieved and should be 0.9–1.0 for passenger cars and 0.5–0.6 for heavy vehicles. Assume a reaction time (T_r) of 2 s.
3	Calculate the maximum possible speed (in km/h) limited by lateral acceleration using the formula: $$V = \sqrt{127R(lateral\_acc + superelevation)}$$
4	4.1 From this speed, calculate the safety factor (SF) using the equation: $SF = 1 + 0.03476V - 0.00004762V^2$ 4.2 Divide the maximum lateral acceleration value by the safety factor (*SF*), and recalculate the speed using the equation in step 3. This is the desirable maximum speed limited by lateral acceleration, V_{acc}. $$V_{acc} = \sqrt{127R\left(\frac{lateral\_acc}{SF} + superelevation\right)}$$
5	5.1 Calculate the sight distance using the equation: $$SD_{acc} = 2R\cos^{-1}\left(\frac{R-O}{R}\right)$$ 5.2 Based on a safety factor of 2, set the braking coefficient (*d*) to half the maximum braking efficiency value. Then, set the stopping sight distance equal to the sight distance calculated above and solve for speed (V_{sight}) in the following stopping distance equation: $$SD_{stop} = SD_{acc} = \frac{T_r V_{sight}}{3.6} + \frac{V_{sight}^2}{254d} \quad \rightarrow \quad V_{sight} = 127d\left(-\frac{T_r}{3.6} + \sqrt{\left(\frac{T_r}{3.6}\right)^2 + \frac{4SD_{acc}}{254d}}\right)$$
6	The maximum desirable speed for the particular vehicle in the curve is the lesser of the two maximum speed values, V_{acc} and V_{sight}.

Variables

R = Curve Radius (m)
O = Offset Distance from center of the lane to the obstruction (m)
T_r = Driver Reaction time (seconds)
d = Braking Coefficient
V = Vehicle Speed (km/h)
SD_{stop} = Stopping Sight Distance
SD_{acc} = Sight Distance
V_{acc} = Desirable maximum speed limited by lateral acceleration (km/h)
V_{sight} = Desirable maximum speed limited by sight distance (km/h)

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

Discussion

Drivers' failure to accurately judge the appropriate driving speed on horizontal curves can have safety consequences. The Fatality Analysis Reporting System (FARS) indicates that 42,815 people were killed in 38,309 fatal crashes on the US highway system in 2002. Approximately 25% of these crashes occurred along horizontal curves. These crashes occurred predominantly on two-lane rural highways that are often not part of the state DOT system. Approximately 76% of curve-related fatal crashes were single-vehicle crashes in which the vehicle left the roadway and struck a fixed object or overturned; conversely only 11% of curve-related crashes were head-on crashes.

Speed selection by drivers on horizontal curves reflects a variety of vehicle, driver, and roadway factors. For example, drivers of vehicles with larger engines, and greater acceleration capacity, approach curves differently than other drivers (*3*). Experienced and middle-aged drivers report less accurate estimates of perceived speed than do younger and less-experienced drivers along roadway curves (*4*). Visual misperceptions may occur when the horizontal curve is combined with a vertical curve. For example, on-road records of vehicle speed were demonstrated to be consistent with a misperception hypothesis on crest combinations (*5*); i.e., the horizontal radius is perceived to be shorter than it actually is. In a safety research study (*6*), relationships of safety to geometric design consistency measures were found to predict speed reduction by motorists on a horizontal curve relative to preceding curve or tangent, average radius, and rate of vertical curvature on a roadway section and ratio of an individual curve radius to the average radius for the roadway sections as a whole. A review of vehicle speed distributions and the variation of vehicle speed around single road curves found that the pattern of variation in vehicle speeds along a road curve was highly dependant on the level of curvature; this effect was more pronounced for curves of radius less than 250 m (*7*). While radius of curvature is not the only factor that influences selected speed on horizontal curves (*8*), it may be the most important factor (*9*).

Determining speeds for horizontal alignment is a complex mix of personal judgment, empirical analysis, and AASHTO/state DOT guidelines. A number of sources provide equations and procedures that reflect the complexity of speed selection on curves by drivers. A series of speed prediction equations for passenger vehicles on two-lane highways as a function of various characteristics of the horizontal curve is provided in Anderson, Bauer, Harwood, and Fitzpatrick (*6*). A series of steps that can be used to determine maximum desirable speed is provided in Charlton and de Pont (*2*).

Design Issues

Transportation Research Circular 414 (*10*) stated factors contributing to higher crash frequency on horizontal curves include higher traffic volumes, sharper curvature, greater central angle, lack of a transition curve, a narrower roadway, more hazardous roadway conditions, less stopping distance, steep grade on curve, long distance since last curve, lower pavement friction, and lack of proper signs and delineation.

Cross References

The Influence of Perceptual Factors on Curve Driving, 6-4

Key References

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COUNTERMEASURES FOR IMPROVING STEERING AND VEHICLE CONTROL THROUGH CURVES

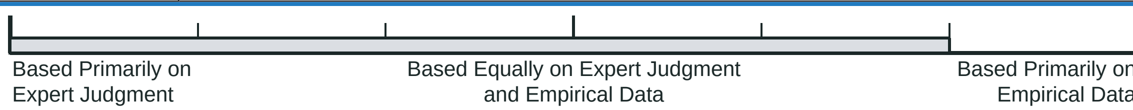
Introduction

Successful navigation of curves depends on accurate steering and speed control in order to minimize lateral acceleration within the lane. Design of alignments that conform to driver expectations and typical behaviors will enhance the driver's ability to control the vehicle. This guideline provides strategies for implementing curve geometries that help drivers maintain proper lane position, speed, and lateral control through curves. Delineation treatments that improve vehicle control are presented in the "Countermeasures to Improve Pavement Delineation" guideline.

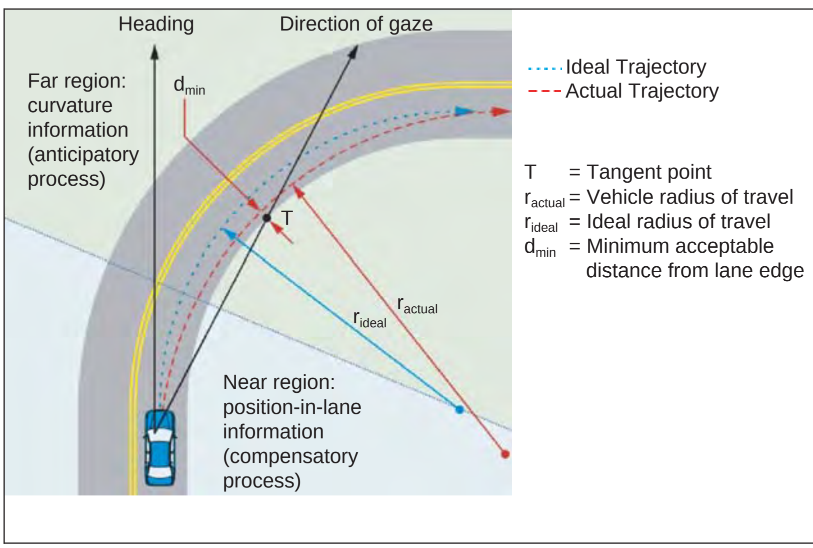
Design Guidelines

The following guidelines present strategies for designing geometric features that will enhance steering control.

Curvature	• Minimize the use of controlling curvature (i.e., maximum allowable curvature for a given design speed).
Spirals	• Spiral transition curves should be used whenever possible, particularly for curves on roads with high design speeds (e.g., 60 mi/h or greater). • Spiral curve lengths should equal the distance traveled during steering time (i.e., 2 to 3 s depending on radius). • The recommended curve radius for two-lane highways with a speed limit of 50 mi/h is 120 to 230 m, with clothoid parameters between 0.33 and 0.5 R.
Reverse Curves	• Do not use tangent sections in reverse curves when the distance between the exit of the first curve and the entrance of the second curve is short enough to encourage a curved path through the tangent (e.g., 80 m or less for two-lane highways and 135 m for freeways).
Superelevation	• Superelevation should be designed to result in zero lateral acceleration through the curve at design speed.
Design Consistency	• Avoid sharp, isolated curves and maintain consistency in the design of superelevation, road width, and other curve features to improve conformance with drivers' expectations.



The figure below illustrates the various concepts that describe how drivers navigate a curve: visual components related to guidance and lane-keeping, the path choice model, and the combination of processes that govern curve traversal.



- Driver enters curve to the left of the lane center
- Far region provides cues for predicting curvature and steering angle in closed-loop anticipatory control process.
- Near region (≤7 degrees down from horizon) provides cues for correcting deviations from path in open-loop compensatory control process.
- Driver follows trajectory with radius of curvature (r_{actual}) greater than radius at center of lane (r_{ideal}) and that brings the vehicle to a minimum distance (d_{min}) from the roadway edge line at its apex.
- Driver fixates on curve tangent point through the curve.

Adapted from Donges (*1*); Levison, Bittner, Robbins, and Campbell (*2*); and Spacek (*3*). Figure not to scale.

Discussion

The steering control task has been modeled as a two-level process composed of an open-loop anticipatory component (far view) for predicting curvature and steering angle, and a closed-loop compensatory component (near view) for correcting deviations from the desired path (*1*). However, this two-level model does not adequately describe some path-decision behaviors such as curve-cutting. Also, drivers often make anticipatory steering actions based on an internal estimate of the vehicle characteristics and on previously perceived curvature, rather than on direct visual feedback, while paying attention to other aspects of the driving task (*4*).

Geometric alignment and delineation features affect the driver's perception of curvature and therefore influence curve entry speed. Curve geometries that do not meet the driver's perceptual expectations may result in inappropriate entry speeds that require speed and steering corrections within the curve in order to avoid excessive lateral acceleration and a potential loss of control. Inaccuracies in anticipatory assessment prior to curve entry generally increase with curvature, and compensatory control actions to correct these errors are greatest in sharp curves (*4*, *5*).

In general, drivers tend to cut curves. In one study (*3*), almost one-third of drivers cut left-hand curves and 22% cut right-hand curves. Drivers compensate for inadequate steering adjustment at curve entry by following a trajectory with a radius that is larger than the ideal radius (i.e., radius at the center of the lane), with the vehicle traveling within some minimum distance of the edge line at its apex (*2*, *7*). Vehicle path radius at the point of highest lateral acceleration correlates with higher crash rates.

Design Issues

Curvature: Road curvature significantly affects average lateral position error. As curves become sharper, there is a corresponding increase in workload, which can result in an increase in edge line encroachments on the inside lane (*6*, *7*). Restrictive geometric characteristics (e.g., sharper curves, narrower shoulders, and steeper grades) are more likely to lead to centerline encroachments than those that are less constraining; however, high curvature has the greatest adverse effect on crash rates and driving performance in horizontal curves.

Spiral curves: Spirals that are designed to match drivers' natural steering behavior offer a gradual increase in centrifugal force and facilitate superelevation transitions, which can improve the vehicle's lateral stability (*6*, *7*, *8*). However, overly long spiral transitions can lead to misleading perception of the sharpness of curvature, inappropriate entry speed, and unexpected steering and speed corrections within the curve. The most desirable spiral length is equal to the distance traveled during the steering time (nominally 2 to 3 s depending on radius).

Reverse curves: Tangent sections of appropriate length can provide effective transitions between curves in a reverse curve alignment. However, if the tangent section is too short, drivers may follow a curved rather than straight trajectory through the tangent section (*7*). To match the alignment to drivers' typical steering behavior, the transitional tangent should be long enough to allow straightening of the vehicle through the transition (if possible); otherwise, the transitional tangent should not be used.

Design consistency: Drivers are more likely to make appropriate speed and steering decisions when the roadway design meets their perceptual expectations. Consistency in curve features, such as superelevation, lane width, curvature, etc., help reduce workload and therefore improve stability in steering control (*6*).

Cross References

The Influence of Perceptual Factors on Curve Driving, 6-4
Speed Selection on Horizontal Curves, 6-6
Countermeasures to Improve Pavement Delineation, 6-10

Key References

1. Donges, E. (1978). Two-level model of driver steering behavior. *Human Factors, 20*(6), 691-707.
2. Levison, W. H., Bittner, A. C., Robbins, T., and Campbell, J. L. (2001). *Development of Prototype Driver Models for Highway Design. Task C: Develop and Test Prototype Driver Performance Module (DPM).* Washington, DC: FHWA.
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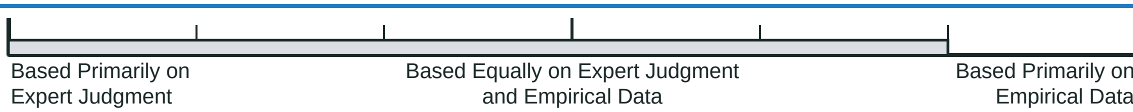
COUNTERMEASURES TO IMPROVE PAVEMENT DELINEATION

Introduction

This guideline describes countermeasures that support improvements in curve detection and driver performance through the use of pavement surface markings, such as edge lines, raised retroreflective pavement markers (RRPM), transverse stripes, etc. These markings provide primarily non-verbal cues that promote improved vehicle control through earlier detection and recognition of curves, reductions in speed, and adjustments to lateral position.

Design Guidelines

General	• Use surface delineations that are characterized by small gaps, long dashes, and short repetition cycles. • Use combinations of treatments wherever practical to increase overall effectiveness.
Edge line/ Centerline	• Use edge lines when curves are sharp or frequent, on narrow roads, or in the vicinity of crossing roadways or major driveways. • Use the widest possible edge lines and centerlines to maximize visible surface area. • When possible, use striping materials with highly retroreflective characteristics to implement edge lines and centerlines.
RRPM	• Combine RRPM with edge lines/centerlines. • Use pairs of RRPM on the outside edges of the centerline for very sharp curves (≥ 12 degrees); for flatter curves, single RRPMs are sufficient. • Place RRPMs 244 m in advance of the curve. Space markers at 40 m intervals for sharp curves and 80 m intervals for flatter curves.
Transverse Stripes	• When practical, implement transverse stripes as graduated rumble strips. • Space stripes to achieve 0.5 s intervals at the desired deceleration rate (e.g., 0.9 m/s^2)
"SLOW" text with arrow	• Use "SLOW" with arrow surface markings in the tangent section approximately 70 m before the curve to augment treatments in high-hazard areas or at sharp curves.



The following table indicates various pavement marking treatments and their strengths for enhancing speed reduction, lane-keeping, and curve detection and recognition.

Treatment Type	Strengths
General – Surface markings	Strongest curvature cues and short-range steering control (compensatory control)
General – Post-mounted chevrons	Strongest guidance cues and long-range guidance (anticipatory control)
Treatment Combinations	Superior effectiveness compared with individual treatments
Edge line/Centerline	Strongest for curve recognition, curvature perception, and reduction of lateral variability. Discontinuities in edge line aid in recognizing upcoming intersections, driveways, etc.
RRPM	Improving visibility of edge lines and centerlines. Reducing lane encroachments. Both visual and rumble effects provide encroachments cues.
Transverse Stripes	Speed reduction. May be more effective at reducing higher (> 85th percentile) speed driving than lower speed driving.
"SLOW" Text with Arrow	Speed reduction and curve ahead warning.

Discussion

Road delineations provide cues that assist drivers in detecting curves and assessing the level of curvature. Road surface markings provide the strongest curvature cues and are best for providing short-range steering control cues (compensatory control—see "Countermeasures for Improving Steering and Vehicle Control Through Curves"), while chevron designs on post-mounted panels give the strongest guidance cues and are best for long-range guidance (anticipatory control). Under conditions of reduced visibility, steering performance improves in the presence of road surface delineations that are characterized by small gaps, long dashes, and short repetition cycles.

Edge lines improve perception of curvature, curve recognition distance, and lane-position stability. Roads with edge lines exhibit fewer crashes than those without edge lines, particularly in combination with narrow widths, wet pavement, and/or high-hazard areas (*1*). Surface area has the greatest effect on edge line (and centerline) visibility—effectiveness increases with wider edge lines. Also, the effectiveness of these stripes increases with the level of retroreflectivity.

Raised reflective pavement markers are highly effective at improving curve visibility and reducing crashes, especially when used in combination with centerlines and edge lines (*2*). They can be particularly useful as a cue for warning of lane encroachment because the raised marker provides tactile as well as visual stimulus. As with edge lines, the effectiveness of RRPMs increases with retroreflectivity.

Transverse stripes refers to painted or taped stripes that are applied perpendicularly across the roadway alignment. Typically, these stripes are separated by decreasingly graduated spacings in order to encourage speed reduction by creating a sensation of increased speed when the vehicle is traveling at constant speed. The effectiveness of transverse stripes has been mixed; while some studies report reductions in speed at curve entry (*3*), others report either no reduction or a slight increase in speed (*4*). Transverse stripes are most effective when implemented as rumble strips because they provide both visual and tactile stimuli.

"Slow" text with arrow refers to the word "Slow" marked in elongated letters with an arrow above it pointing in the direction of the curve and transverse lines before and after the symbols. This treatment may be effective at speed reduction, especially in late night driving when drivers are more likely to be impaired by fatigue or alcohol (*5*).

Combinations of treatments are generally more effective than any single treatment, especially when the combination includes rumble strips. Curve recognition, lane position, and number of encroachments are improved when RRPMs are used in conjunction with edge line/centerline markings compared with single treatments.

Design Issues

In general, centerline treatments tend to cause drivers to shift lateral position away from the centerline, while edge line treatments result in a lateral shift toward the centerline. RRPMs may reduce nighttime corner cutting in left-hand curves but increase corner cutting in right-hand curves (*6*).

Several treatments, such as transverse stripes and widening of inside edge markings at the curve, may have a greater effect on driver performance for high-speed drivers (above 85th percentile speeds) than for lower-speed drivers. These treatments should be considered in hazard areas where speed is a prevalent factor in elevated crash rates (*3*).

Cross References

Speed Selection on Horizontal Curves, 6-6
Countermeasures for Improving Steering and Vehicle Control Through Curves, 6-8

Key References

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SIGNS ON HORIZONTAL CURVES

Introduction

Prior to a change in the horizontal alignment of a roadway, information about this change should be conveyed to drivers via roadway signs. This information should be communicated in a concise and efficient manner such that drivers have time to process the information and adjust their speed as well as alter the vehicle path appropriately. Notification of an upcoming curve is typically conveyed using curve warning signs, which indicate whether the curve is to the right or the left; they are sometimes accompanied by advisory speed signs. The use of dynamic warning signs to alert drivers of a curve and/or their vehicle speed has also gained acceptance as an effective means of communication.

Researchers disagree as to how advance warnings should be presented to drivers, i.e., through text or through symbols. But all agree that the key to effective warning is to notify the driver of the upcoming curve so that the driver can change the speed or path of the vehicle—or both. Individual studies on the effectiveness of advance warning signs vary considerably with respect to sign placements, sign messages, horizontal curve radii, and driver populations. Designers should consider such variables when making design decisions. Also, any information considered for use in curve signs should not be in conflict with current design standards in publications such as the MUTCD.

Design Guidelines

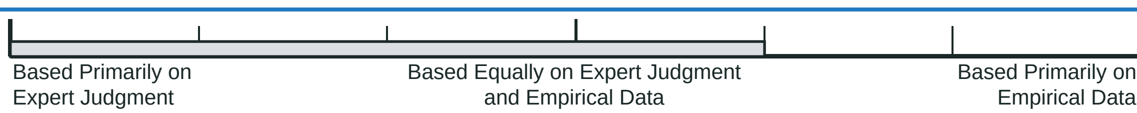
The tables below show the guidelines for advance placement of curve warning signs related to advisory/85th percentile speed, as well as spacing for chevrons—both are presented as a function of posted or advisory speeds (Adapted from McGee and Hanscom (*1*)).

Posted or 85th Percentile Speed (mi/h)	Advance Placement Distance (ft) for Advisory Speed of the Curve (mi/h) of						
	10	20	30	40	50	60	70
20	n/a[1]	–	–	–	–	–	–
25	n/a[1]	n/a[1]	–	–	–	–	–
30	n/a[1]	n/a[1]	–	–	–	–	–
35	n/a[1]	n/a[1]	n/a[1]	–	–	–	–
40	n/a[1]	n/a[1]	n/a[1]	–	–	–	–
45	125	n/a[1]	n/a[1]	n/a[1]	–	–	–
50	200	150	100	n/a[1]	–	–	–
55	275	225	175	100	n/a[1]	–	–
60	350	300	250	175	n/a[1]	–	–
65	425	400	350	275	175	n/a[1]	–
70	525	500	425	350	250	150	–
75	625	600	525	450	350	250	100

[1] No suggested distance is provided for these speeds, as the placement location depends on site conditions and other signing to provide an adequate advance warning for the driver.

Advisory Speed Limit (mi/h)	Chevron Spacing (ft)
15	40
20	80
25	80
30	80
35	120
40	120
45	160
50	160
55	160
60	200
65	200

NOTE: The above spacing distances apply to points within the curve. Approach and departure spacing distances are twice those shown above.



Discussion

Numerous studies have shown the effectiveness of advanced warning signs for curves (*2*, *3*, *4*, *5*). Typical improvements in driving performance are reductions in speed, fewer lane excursions, and generally fewer crashes—see also the table below. From a driver's perspective, the key advantage of advance warning signs is a notification that a (possibly) unexpected change in the horizontal alignment of the roadway is imminent. Signing can be used to notify the driver of an upcoming curve in many ways, including proper positioning along a driver's line of sight, fluorescent illumination, flashing beacons (*5*), or dynamic warnings. In this regard, designers are cautioned to avoid overloading the driver with extraneous information that might distract him or her from the primary task of maintaining safe control of the vehicle (*6*).

Improvement	Reference	Findings
Fluorescent Yellow Microprismatic Chevron Treatments	*2*	Weighted average decrease in speeds at the curve point of curvature of about 1 mi/h for both the mean and 85th percentile versus the existing standard yellow ASTM Type III signs. 38% overall reduction in edge line encroachments.
Fluorescent Yellow Chevron Posts	*2*	Speeds reduced slightly.
Fluorescent Yellow Microprismatic Curve Warning Signs	*2*	The overall number of vehicles initiating deceleration before reaching the curve warning sign was increased by 20%. However, the study found small and inconsistent effects on speeds approaching curves.
Standard Red Reflectorized Border on Speed Limit Sign	*2*	The red border had the greatest effect on speeds during the day for both passenger vehicles and heavy trucks. Daytime mean and 85th percentile speeds of heavy trucks were found to decrease by ≈ 4 mi/h.
Addition of Flags, Flashers on Existing Warning Signs	*3*	The changes made to roadway surface included more reflective centerlines (CLs), more reflective edge lines (ELs), wider ELs, the additional of raised retroreflective pavement markers, and the inclusion of horizontal signing warning of approaching curves.
Dynamic Advance Curve Warning System	*4*	Results found decreases in mean speeds from 2 to 3 mi/h.
Different Pavement Markings and Raised Retroreflective Pavement Markers	*5*	Nighttime average speed reductions for the warning sign with flashing lights (5.1%), the combination horizontal alignment/advisory speed sign (6.8%), and flashing lights on both warning signs (7.5%).

Design Issues

In a literature synthesis of the knowledge and practice, the physical and performance characteristics of heavy vehicles that interact with highway geometric design criteria and devices were examined (*7*). The synthesis notes that dynamic curve warning systems for trucks—especially highly accurate, sophisticated systems that incorporate vehicle parameters such as speed and weight—may help warn drivers of curves ahead and mitigate rollover crashes.

Cross References

Speed Selection on Horizontal Curves, 6-6

Key References

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3. Molino, J., Donnell, E. T., and Opiela, K.S. (2006). Field ratings of nighttime delineation enhancements for curves. *Transportation Research Board 85th Annual Meeting Compendium of Papers* [CD-ROM].
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6. Zwahlen, H. T. (1987). Advisory speed signs and curve signs and their effect on driver eye scanning and driving performance. *Transportation Research Record, 1111*, 110-120.
7. Harwood, D. W., Potts, I. B., Torbic, D. J., and Glauz, W. D. (2003). *CTBSSP Synthesis of Safety Practice 3: Highway/Heavy Vehicle Interaction*. Washington, DC: Transportation Research Board.

CHAPTER 7

Grades (Vertical Alignment)

DESIGN CONSIDERATIONS FOR TURNOUTS ON GRADES

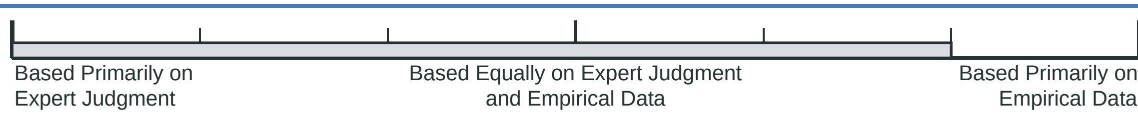
Introduction

Turnouts are widened, unobstructed shoulder areas that allow slow-moving vehicles to pull out of the through lane to give passing opportunities to following vehicles (*1*). This guideline provides design recommendations that support safe and appropriate use of *Turnouts on Grades*. Turnouts are also beneficial for two-lane highways in mountainous terrain. To promote safe use, turnouts should be designed with elements that inform drivers of the presence of the turnout, encourage drivers to enter at safe speeds, encourage users to allow all trailing vehicles in the platoon to pass, and provide adequate sight distance of the lane (behind the vehicle) to safely merge back onto the roadway.

Design Guidelines

The following turnout design recommendations should be considered in order to promote driver behavior that is consistent with safe use of turnouts.

Entry/Exit	Topic	Recommendations
Turnout Entry	Signage	• Use signs at turnouts to: – Notify drivers of an upcoming series of turnouts (*2*). – Notify drivers of a specific turnout (*2*, *3*). – Remind drivers of the legal requirements for turnout use (*3*). – Identify the beginning of a specific turnout (*3*). • If a turnout is to be signed, it is recommended that both an advance sign and a turnout sign be used (*2*). • Do not place an advance sign too far in advance of the turnout. One source suggests 500 to 800 ft may be appropriate (*2*). • Include an upward-sloping arrow (e.g., MUTCD sign R4-14) to indicate that slow-moving vehicles should move to the right (*3*, *4*).
	Sight Distance	• Locate turnouts with adequate sight distance to the entrance to allow time to decelerate to a safe entry speed (*1*). • Avoid locating a turnout on or adjacent to a horizontal or vertical curve that limits sight distance in either direction. The available sight distance should be at least 300 m (1,000 ft) on the approach to the turnout (*1*).
	Entry Speed	• Approach speeds are a function of grade and horizontal alignment. Turnouts on downgrades with gentle curves should be longer than turnouts on steep upgrades with continuous curves (*2*). • When possible, avoid placing turnouts on fill slopes or drop-offs, particularly on the outside of curves. Turnouts on these geometries can appear very small to high-speed drivers, discouraging their use (*2*).
Turnout Exit	Sight Distance	• Locate turnouts with adequate sight distance to the exit so that approaching drivers can see low speed vehicles leaving the turnout (*2*). • Use the Guideline in Chapter 10: *Sight Distance at Right-Skewed Intersections* for design considerations related to site distance for drivers exiting the turnout.
	Exit Behavior	• Avoid excessively long turnouts to discourage drivers from using it as a passing lane and cutting back into the platoon (*1*, *2*).



Discussion

Turnouts may be utilized more by recreational vehicles and slower passenger cars, while heavy truck drivers are not likely to use them at all (*2*). Turnouts are most frequently used on lower volume roadways where long platoons are rare and in difficult terrain with steep grades where placement of additional lanes is not cost-effective. Over 80% of all following vehicles in platoons immediately behind a turnout user are generally able to pass the turnout user.

A pass completed because of a turnout maneuver may not provide as much operational benefit as a pass completed in a passing lane (*4*). In a passing lane, the passing vehicles are self-selected, with higher desired speeds than their immediate platoon leader. By contrast, turnout users (rather than the passing vehicles) are self-selected, and the passing drivers may or may not have higher desired speeds. The passing vehicles at a turnout may simply continue downstream as a new platoon leader. Therefore, it is expected that a turnout may not provide as much reduction in platooning per passing maneuver as a passing lane.

Design Issues

Turnouts are most effective if their purpose is clearly conveyed to roadway users by appropriate signing and turnout placement. In one study (*4*), the signage that provided the greatest degree of positive guidance included an upward-sloping arrow indicating that slow-moving vehicles are to move to the right. Signage may also be effective for deterring drivers from utilizing turnouts as rest areas or scenic stopping points.

When warning drivers of an upcoming turnout, it is recommended that two signs be placed: an advance warning sign and a location sign; however, the advance sign should not be placed too far in advance of the turnout. In one study (*2*), some vehicles stopped at areas other than the turnout when the advance sign was one-quarter mile from the turnout.

Vehicle drivers that lead long platoons drive more slowly into the turnout when compared to those leading short platoons (*4*). In contrast, short platoon leaders that utilize turnouts enter with higher speeds that can be dangerous to any vehicle that is occupying the turnout. Designers should realize that vehicles could enter the turnout at speeds up to 50 mi/h and design the length of the turnout accordingly, accounting for grade and curvature. Turnouts on fill slopes or drop-offs can appear very small to high-speed drivers (particularly when located on the outside of a curve), which may discourage their use.

Turnouts of inadequate length may be used only infrequently. In one study, turnouts with low safe-entry speed due to their short length of 200 ft were never used (*4*). However, if the turnout is too long, it may be used as a passing lane rather than a turnout. Average speeds of 26 to 31 mi/h have been observed within some longer turnouts (*2*). In that study, turnout lengths of 200 to 250 ft appeared to be suitable for low-speed roads (30 mi/h or less), while lengths of about 400 to 450 ft appeared suitable for high-speed roads (e.g., 50 mi/h). These lengths are generally consistent with those found in the Green Book (*1*).

It is customary to find turnouts in mountainous regions but they should not be located where horizontal or vertical curves limit sight distance. Turnouts can be added to rural roadways to increase passing opportunities where available sight distance is at least 300 m (approximately 985 ft) on the approach to the turnout. In any case, the turnout must be designed with sufficient sight distance for approaching drivers to see and react to vehicles leaving the turnout at slow speeds.

Exiting from a turnout is similar to navigating a right-skewed intersection. The guideline "Sight Distance at Right-Skewed Intersections" (page 10-8) can be used to determine the available sight distance for drivers who are leaving the turnout. However, any horizontal curvature in the roadway approaching the turnout should be considered when determining the skew angle.

Cross References

Sight Distance at Right-Skewed Intersections, 10-8

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.
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GEOMETRIC AND SIGNING CONSIDERATIONS TO SUPPORT EFFECTIVE USE OF TRUCK ESCAPE RAMPS

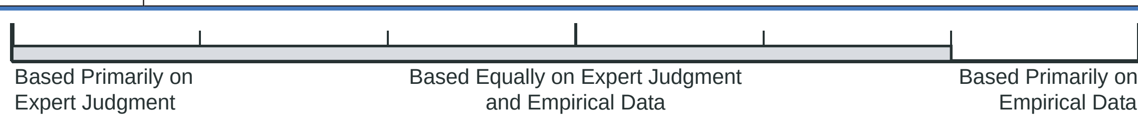
Introduction

A *Truck Escape Ramp* (TER) is a facility designed and constructed to provide a location for out-of-control trucks (though other vehicles can use them as well), to slow and stop away from the main traffic stream. Out-of-control vehicles are generally caused by a driver losing the ability to brake, either through overheating of the brakes due to mechanical failure or failure to downshift at the appropriate time. Multiple terms can be used to describe this family of ramps including truck escape ramps, emergency escape ramps, safety ramps, runaway lanes, arrester beds, or gravity lanes. TERs typically slow out-of-control vehicles by dissipating their energy through gravitational deceleration, rolling resistance, or both. AASHTO (*1*) provides comprehensive guidance regarding the design and location of emergency escape ramps; this guidance is provided in the "Element of Design" chapter.

Design Guidelines

Consideration should be given to the following geometric and signage aspects of TER design to promote driver behavior that is consistent with safe use of escape ramps:

Topic	Guideline
Geometric	• A TER should be designed such that the driver of a runaway truck can see the entire ramp (or at least a significant portion of it). • If a service road is developed adjacent to an escape ramp, the design of the ramp and service road should be distinct so that drivers of out-of-control vehicles will not mistake the service road for the ramp. Providing sufficient sight distance will help eliminate any possible confusion (*2*). • When truck drivers have the option of two escape ramps on a given downgrade, the lower ramp is typically preferred over the first and higher elevation ramp. • Ensure that the ramp cannot mistakenly lead other motorists from the mainline (*3*). • Operators lose their steering capability upon entering an arrester bed, thus escape ramps should be straight and their angle to the roadway should be as flat as possible (*2*).
Signing	• Advance signing is necessary to inform drivers of the existence of the ramp, and access to the ramp should be made obvious by exit signing (*1*). • "Runaway Vehicles Only" and "No Parking" signs adjacent to escape ramps may be useful in ensuring other vehicles do not block escape ramps by entering or parking in front of the ramp. • Generic message signs located at the roadside typically have less impact than advisory signs that target specific at-risk vehicles (*4*). • Weight-Specific-Speed (WSS) signs should have no more than five weight classes posted; this will limit driver confusion from too much information (*5*). • Minimal, standard, or briefing signs can lead drivers to underestimate the severity of the severe grades and overestimate the severity of the benign ones. These estimates can result in potentially dangerous brake over-heating on severe grades in addition to overly cautious and slower driving on non-severe grades (*6*).



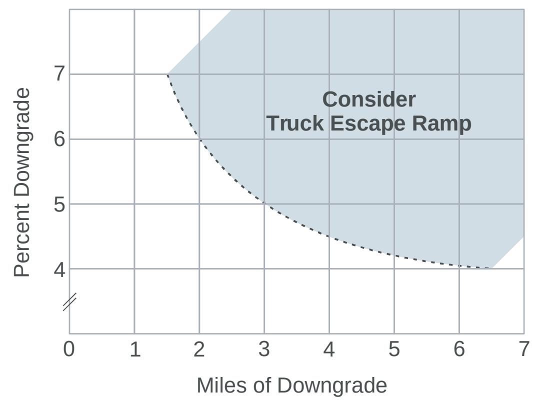
Discussion

As noted on the previous page, AASHTO (*1*) provides comprehensive guidance regarding the design and location of emergency escape ramps in the "Element of Design" chapter. This guideline merely emphasizes key aspects of the Green Book (*1*) guidance and adds guidance from additional sources.

Design Issues

On existing roadways, a field review, crash experience, and/or documentation from law enforcement agencies can be used to assess the need for a TER. Another tool that can be used to assess the need for TERs on new and existing roadways is the *Grade Severity Rating System,* which is a simulation model that establishes a safe descent speed for the grade based upon a predetermined brake temperature limit. Where brake temperatures exceed the predetermined limit, the potential for brake loss exists, indicating that a TER may be necessary. The Arizona Department of Transportation (*7*) provides the following graph in their *Roadway Design Guidelines* to use to determine if a TER is needed.

CONSIDERATION OF TER VS. LENGTH AND PERCENTAGE OF DOWNGRADE



Source: Adapted from Arizona Department of Transportation (*7*)

Cross References

Sight Distance Guidelines, 5-1
Special Considerations for Rural Environments Guidelines, 16-1
Speed Perception, Speed Choice, and Speed Control Guidelines, 17-1
Signing Guidelines, 18-1
Markings Guidelines, 20-1

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.
2. Witheford, D.K. (1992). *NCHRP Synthesis of Highway Practice 178: Truck Escape Ramps*. Washington, DC: Transportation Research Board.
3. Ballard, A.J. (1983). Current state of truck escape-ramp technology. *Transportation Research Record, 923*, 35-42.
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PREVIEW SIGHT DISTANCE AND GRADE PERCEPTION AT VERTICAL CURVES

Introduction

The *preview sight distance* (PVSD) is a measure of driver sight distance based on the assumption that "the driver views or previews the roadway surface and other cues that lie ahead to obtain the information needed for vehicular control and guidance" (*1*). It is based on the assumption that a driver requires a minimum PVSD to perceive and respond to upcoming alignment cues. The PVSD applies directly to horizontal curves near the top of crest vertical curves (or at the bottom of sag vertical curves), in which the horizontal curve is initially out of the driver's line of sight. The AASHTO Green Book (*2*) recommends avoiding these situations but provides no specific design values.

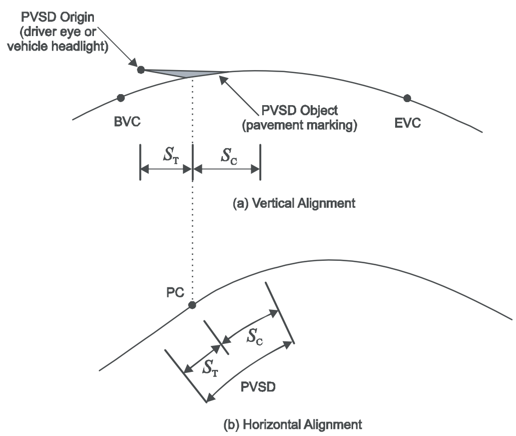
Design Guidelines

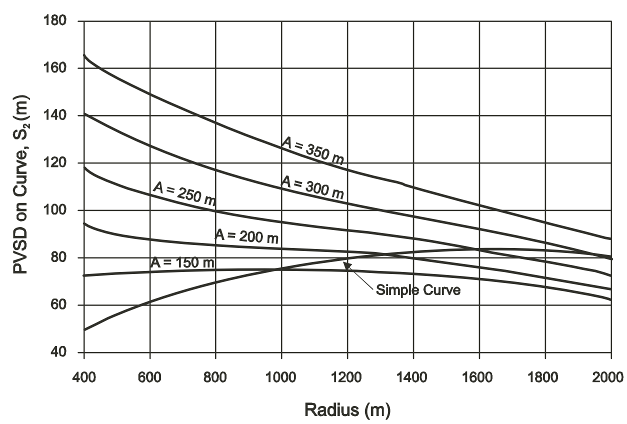
Design values of required PVSD are shown in the table below for horizontal curves of different radii on level grades (for a simple curve and with spiral transitions of different "flatness," i.e., spiral parameter A). S_T indicates the PVSD on the road section prior to the curve section (i.e., tangent section immediately preceding a simple curve), and S_C indicates PVSD on the curve section (see figure).

Horizontal Curve Radius (m)	Required PVSD (m)*							
	Simple Curve		Spiraled Curve					
			A** = 100 m		A = 200 m		A = 300 m	
(1)	S_T (2)	S_C (3)	S_T (4)	S_C (5)	S_T (6)	S_C (7)	S_T (8)	S_C (9)
400	131	50	107	57	66	93††	66	119††
600	110	62	94	63	66	88	66	119††
800	99	70	87	70†	66	86	66	117
1,000	93	76	83	76†	66	84	66	109
1,200	88	80	80	80†	66	83	66	103
1,400	85	83	78	83†	66	83†	66	98
1,600	83	83	77	83†	66	83†	66	92
1,800	81	83	76	83†	66	83†	66	86
2,000	80	81	75	81†	66	81†	66	81†

* Values rounded to next integer;
** A is the square root of the product of radius and distance from the beginning of a spiral
† Minimum value;
†† Maximum value

Illustration of PVSD on a crest vertical curve (left). S_T is the driver's reaction distance (PRT) that falls on the roadway section prior to the point of curvature (PC) of the horizontal curve, and S_C is the amount of horizontal curvature required to make the curve detectable to the driver. Calculated minimum values of S_C are shown on the right.





BVC=Beginning of Vertical Curve; EVC=End of Vertical Curve

Figures recreated from Hassan and Easa (*3*).

Discussion

The PVSD reflects sight distance needs apart from the typical sight distance requirements, such as stopping sight distance, decision sight distance, passing sight distance, and intersection sight distance. In particular, it addresses the adequate view of the roadway alignment, pavement surface, and other features that provide the vehicle control and guidance cues that drivers need to have a relaxed, comfortable, and safe ride (*1*). The PVSD can be considered a special case of the decision sight distance (*3*). In addition to horizontal curves following vertical curves, the PVSD can also apply to horizontal curves that are obscured by the surrounding topography, such as rock cuts, and to road segments directly preceding elevated freeway exit ramps.

Conceptually, PVSD is the length of roadway traveled while the driver perceives and reacts to upcoming roadway guidance cues. It has practical importance with regard to horizontal curves that follow vertical curves because tangents usually have higher operating speeds than horizontal curves, and drivers may have to decelerate before entering the horizontal curve. The PVSD helps ensure that drivers have sufficient time to perceive the horizontal curve and to lower their speed by accounting for the sight distance restrictions caused by the vertical curvature.

The PVSD has two components. The first is the distance associated with drivers' perception-reaction time that falls on the roadway prior to the point of curvature of the horizontal curve (S_T), and the second is the amount of the curve that must be visible for drivers to detect the horizontal curve (S_C). If the tangent section transitions directly before the curve without a spiral, then the PRT distance should be accommodated fully within the tangent section and end before the curve. If the curve is preceded by a spiral transition, then the PRT distance can lie on the spiral and extend to the tangent if necessary. This leads to a trade-off. In particular, sharp curves (i.e., simple curves) require that a shorter segment be visible for the curvature to be detectable (smaller S_C); however, more deceleration distance may be necessary to accommodate a larger speed change (longer S_T). In contrast, since spiral curves are more gradual, they should require that more of the curve be visible for it to be detectable (longer S_C), but the deceleration distance can be included in the spiral length, which leads to a shorter S_T distance.

Under daylight conditions, the PVSD is calculated as the line of sight from the driver's eye to a point that intercepts and is tangent to the curvature of the pavement surface. The guideline information is based on analytical modeling of the PVSD (*3*, *4*), and the guideline table shows PVSD calculations for S_T and S_C for various values of curvature radius and spiral parameter A (a measure of the flatness of the spiral). At low values of A and high radius values (R), the analytical modeling yielded non-applicable results since spiral curves should always be flatter than simple curves and consequently have PVSD values that are at least as long as for a simple curve (i.e., the curvature of a spiral curve should be more difficult to detect; see figure on the previous page). Accordingly, the required S_C for spiral curves (bottom entries in columns 5, 7, & 9) are assigned the value of S_C for the corresponding simple curves in these cases (i.e., column 3). Speed was modeled assuming a tangent speed of approximately 60 mi/h, with curve operating speed calculated based on the indicated curve radius (R). The deceleration level was assumed to be 0.85 m/s^2. Note that the analytical work conducted to develop the guideline table was limited to separate horizontal curves on level grades. Also, the authors caution that the design values for the table are only applicable to the range of horizontal radii investigated in their experiment (i.e., those shown in the table).

Design Issues

Time of day is an important consideration. In particular, daytime driving should use the line of sight from the driver's eye to the pavement marking. However, at night, sight distance is limited by headlamp illumination of the pavement markings, which means that the line of sight should be to the reference vehicles' headlamp height.

Cross References

Sight Distance Guidelines, 5-1
Curves (Horizontal Alignment), 6-1
Nighttime Driving, 21-4

Key References

1. Gattis, J.L., & Duncan, J. (1995). Geometric design for adequate operational preview of road ahead. *Transportation Research Record, 1500,* 139-145.
2. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.
3. Hassan, Y., & Easa, S.M. (2000). Modeling of required preview sight distance. *Journal of Transportation Engineering, 126*(1), 13-20.
4. Hassan, Y., & Easa, S.M. (1998). Design considerations of sight distance red zones on crest curves. *Journal of Transportation Engineering, 124*(4), 343-352.

CHAPTER 8

Tangent Sections and Roadside (Cross Section)

Tangent sections and related design aspects are not topics that are typically examined separately in human factors or driver behavior research. Consequently, the current chapter only has a few guidelines on this topic. However, as a basic roadway element, tangents are often a relevant contributing aspect to a variety of driver factors. The HFG reflects this in other chapters with several guidelines directly relevant to tangent sections. The table below provides an index of where to find these guidelines within the HFG.

Page Number	Guideline Title	Relevance
5-2	Key Components of Sight Distance	Determining sight distance requirements for tangent sections.
5-4	Determining Stopping Sight Distance	
5-8	Determining When to Use Decision Sight Distance	
5-10	Determining Passing Sight Distance	Passing sight distance recommendations based on design speed and assumed vehicle speeds.
9-2	Perceptual and Physical Elements to Support Rural-Urban Transitions	Recommended measures for controlling driver speed in rural-urban transition zones.
16-2	Passing Lanes	Recommended values of length and spacing by ADT and terrain.
16-4	Countermeasures for Pavement/shoulder Drop-offs	Vertical drop-off heights warranting traffic control for various lane widths.
16-6	Rumble Strips	Recommended sound levels for rumble strips, and effects of different rumble strip characteristics.
17-4	Speed Perception and Driving Speed	Factors that affect speed perception and speed selection.
17-6	Effects of Roadway Factors on Speed	
17-8	Effects of Posted Speed Limits on Speed Decisions	
21-2	Countermeasures for Mitigating Headlamp Glare	Countermeasures for addressing glare from oncoming vehicles in tangent sections.

TASK ANALYSIS OF LANE CHANGES ON TANGENT SECTIONS

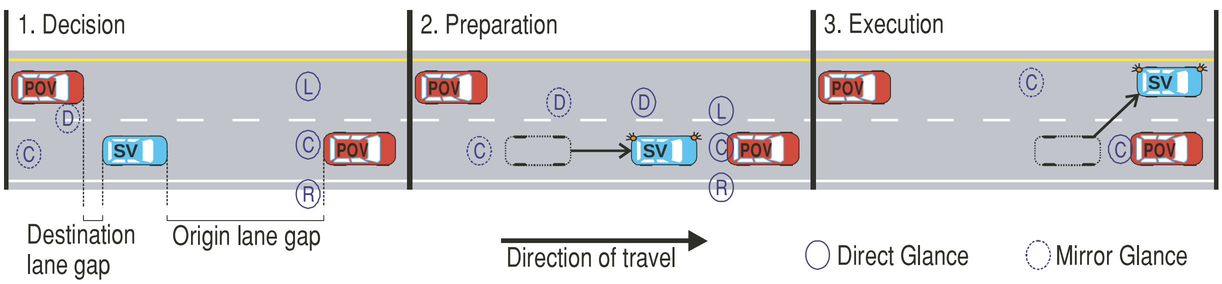
Task analysis of lane changes provides a general description of the tasks involved with making a lane change (LC) on a tangent section of roadway. These tasks are primarily cognitive, motor, visual, or some combination thereof. The tasks apply to many roadway conditions, but the likelihood of their occurrence and manner in which drivers perform them vary based on the individual driver. This task overview has implications for interchange design, and particularly sign placement.

Design Guidelines

Avoid presenting drivers with sign reading or decision-making tasks at locations where lane changes are likely, i.e., entrances, exits, merges, weaving.

Based Primarily on Expert Judgment	Based Equally on Expert Judgment and Empirical Data	Based Primarily on Empirical Data

The figure and table below show the different segments in a lane change as well as the cognitive, motor, and visual workloads associated with the tasks (adapted from Lee, Olsen, and Wierwille (1)).



	1. Decision	2. Preparation	3. Execution
Segment Goal	Decide if a lane change is possible	Prepare vehicle position and turn signals	Steer the lane change maneuver
Key Tasks	1.1 Scan traffic (L,C,R) and TCDs 1.2 Check mirrors (D,C) 1.3 Check memory and assumptions	2.1 Scan forward view (L,R) to verify vehicle is centered 2.2 Maintain safe gap in original lane 2.3 Arrange safe gap in destination lane 2.4 Activate turn signal 2.5 Perform final glances to mirrors (D,C) and blind spots	3.1 Initiate LC maneuver 3.2 Steering (D, beside C) 3.3 Deactivate turn signal 3.4 Check rearview mirror
Driver Factors	• 73-88% of participants underestimate time required	• Approximate probability of: – Turn signal activation: 77-78% – Directional mirror glance: 87% (L), 49% (R) – Inside mirror glance: 42% (L), 78% (R) – Blind spot glance: 31% (L), 16% (R)	N/A
Cognitive Load	**High**	**Low**	**Low**
Motor Load	**Low**	**Low to Medium**	**High**
Visual Load	**High**	**High**	**Medium**

Legend: L = Left, C = Center, R = Right, D = LC Direction

Discussion

The key tasks outlined in the table on the previous page (*1*) depict a general progression of tasks as drivers execute lane changes. The tasks are shown in a vertical column, corresponding to the lane change segment in which they occur. Each segment also has driver factors, which are relevant behavioral information, further described below. The cognitive, motor, and visual workloads are rated and color coded depending on the demand of those resources during the corresponding segment.

The first segment is the decision of whether a lane change is possible. This segment places the highest demands on cognitive activity, mainly related to the decision to initiate the activity. One subtask for drivers involves checking their memory and assumptions related to the lane change task. In an on-road study, most drivers underestimated the amount of time that a freeway lane change actually takes (*2*). The underestimation was more common for lane changes to the right (88% of drivers) than to the left (73% to the left).

After deciding that a lane change is possible, the preparation for the lane change begins. In this second segment, visual and motor tasks dominate. The tasks are centered around arranging a safe gap for the maneuver and preparing for the actual movement. In a study of driver-side blind alert systems, the probability of turn signal activation was 77% and 78% for left and right lane changes, respectively (*3*). In the same study, for left lane changes, the approximate probability of drivers performing a left-mirror glance was 87%, an inside-mirror glance was 42%, and an over-the-left-shoulder glance was 31%. For right lane changes, the approximate probability of drivers executing a right-mirror glance was 49%, an inside-mirror glance was 78% and an over-the-right-shoulder glance was 16%. In their study of naturalistic lane changes, Lee, Olsen, and Wierwille (*1*) found somewhat lower probabilities for the driver glance and turn signal behaviors; however, their analysis was of a set of critical and urgent lane changes, during which drivers may be less inclined to take the time to perform their usual routine.

Once the driver has prepared the vehicle and its position to allow for the lane change, they execute the motor component. In this segment, drivers perform the actual steering involved in the maneuver. Following this step, drivers return to their normal driving behaviors.

The distribution of tasks among the modalities has implications for interchange design, particularly for sign placement. Some areas of interchanges are more likely to systematically involve a higher frequency of lane changes due to geometric features such as entrances, exits, merge/weave sections, and upcoming divergences. From this task analysis, it appears that the cognitive load is highest at the beginning. This load is followed by a series of uninterruptable visual activities to arrange appropriate gaps and monitor surrounding traffic. Since the traffic flow is dynamic, drivers need to resolve these visual activities at the point when motor activities are initiated (i.e., if interrupted, they may need to visually re-check their surroundings to determine if the conditions have changed). One of the implications of these conditions is that signs near high-frequency merge locations may be less likely to be read by merging drivers who are otherwise occupied with visual activities. Therefore, key signs should not be located in such locations.

Design Issues

None.

Cross References

Determining Passing Sight Distance, 5-10

Key References

1. Lee, S.E., Olsen, E.C.B., & Wierwille, W.W. (2004). *A Comprehensive Examination of Naturalistic Lane-Changes* (DOT HS 809 702). Washington, DC: National Highway Traffic Safety Administration.
2. Lerner, N.D., Steinberg, G.V., & Hanscom, F.R. (2000). *Development of Countermeasures for Driver Maneuver Errors* (FHWA-RD-00-022). McLean, VA: FHWA.
3. Kiefer, R.J., & Hankey, J.M. (2008). Lane change behavior with a side blind zone alert system. *Accident Analysis and Prevention, 40*(2), 683-690.

OVERVIEW OF DRIVER ALERTNESS ON LONG TANGENT SECTIONS

Introduction

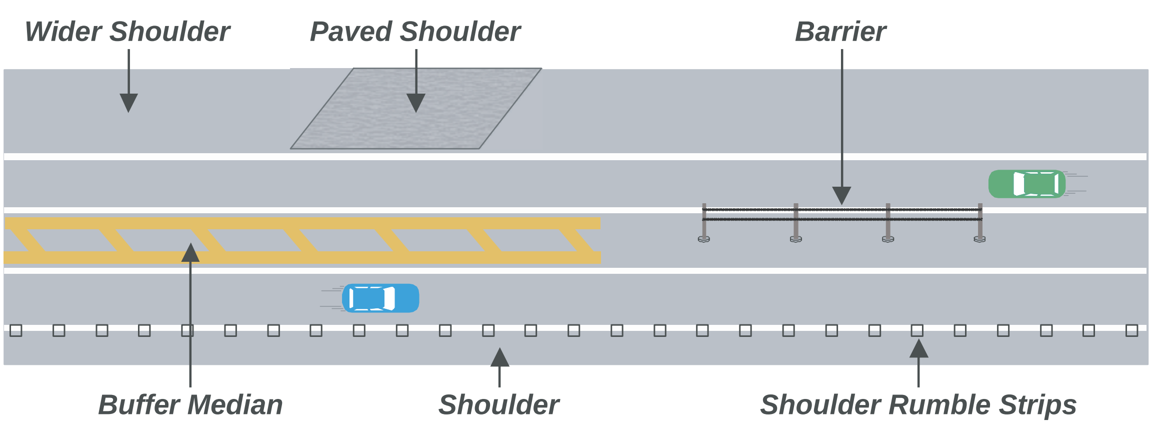
This guideline addresses *driver fatigue and alertness on long segments of straight roadways*. Driver fatigue is defined as a general psycho-physiological state that diminishes an individual's ability to perform the driving task by reducing alertness and vigilance (*1*). Since long monotonous tangents have low levels of physical driving demand and reduced visual stimulation, they may induce driver fatigue and boredom, and reduced alertness. The key design issue in this case is that these types of roads may be "fatigue inducing" because they demand drivers do relatively little in terms of vehicle control and visual scanning.

Design Guidelines

From Stutts et al. (*2*): If long tangent sections are used, consideration should be given to adding countermeasures to prevent crashes or reduce crash severity, including:

- Install shoulder and/or centerline rumble strips
- Eliminate shoulder drop-offs
- Widen and pave shoulders
- Widen two-lane roads and include a narrow "buffer" median between opposing lanes
- Install median barriers for narrow medians on multi-lane roads
- Minimize overturning by designing safer slopes/ditches and removing hazardous roadside obstacles
- Reduce severity of run-off-road crashes through improved roadside hardware and barrier/attenuation systems

EXAMPLES OF COUNTERMEASURES FOR LONG TANGENT SECTIONS



Discussion

Volume 14 of *NCHRP Report 500* (*2*) provides a helpful overview of the problem associated with drowsy drivers, as well as several roadway design strategies that can be used to reduce the problem. The guidelines presented here primarily reflect this recent data source.

Overall, there is a lack of on-road or crash data studies that directly examine the link between tangent length/monotony with fatigue-related safety risk. The issue of tangent length and fatigue is difficult to parse out from general fatigue related to more driver-specific causes such as sleep disruption, time of day, etc. Overall, the empirical data are not definitive regarding the relationship between length or monotony of a tangent, and fatigue-related crash risk. Nonetheless, in addition to countermeasures aimed at reducing the negative consequences of fatigue-related crashes, another logical type of countermeasure involves increasing driver stimulation, such as adding visual complexity or vehicle-control requirements (e.g., a horizontal curve). Most of the pertinent data in this area have been generated from driving simulator research. For example, in an exploratory study, drivers were found to be more likely to make large steering wheel movements on a visually monotonous roadway, which was interpreted as being fatigue related (*1*). In another study, the most apparent fatigue symptoms occurred on straight roads, or straight sections of roads with a mix of straight and curved elements (*3*). Tying these findings in with on-road data, a 100-car naturalistic driving study found that 56% of run-off-road events occurred on straight segments of roadway (*4*), suggesting countermeasure treatments would be desirable.

Design Issues

This guideline focuses on roadway design interventions to address driver fatigue on long tangent sections of roadway and task-induced fatigue rather than sleepiness. Driver alertness due to the impact of monotonous roadways is just a small part of the larger topic of driver fatigue as caused by sleepiness or drowsiness. There are a number of data sources related to this broader issue, especially in the context of long-haul truck and other commercial drivers. There are also a number of sources that describe risk factors associated with driver fatigue and countermeasures that can be used to reduce driver fatigue (*5*).

Cross References

Rumble Strips, 16-6

Key References

1. Thiffault, P., & Bergeron, J. (2003). Monotony of road environment and driver fatigue: A simulator study. *Accident Analysis & Prevention, 35,* 381-391.
2. Stutts, J., Knipling, R.R., Pfefer R., Neuman, T.R., Slack, K.L., & Hardy, K.K. (2005). *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 14: A Guide for Reducing Crashes Involving Drowsy and Distracted Drivers.* Washington, DC: Transportation Research Board.
3. Oron-Gilad, T., & Ronen, A. (2007). Road characteristics and driver fatigue: A simulator study. *Traffic Injury Prevention, 8*(3), 281-289.
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CHAPTER 9

Transition Zones Between Varying Road Designs

PERCEPTUAL AND PHYSICAL ELEMENTS TO SUPPORT RURAL-URBAN TRANSITIONS

Introduction

Rural-urban transition zones occur in areas where high-speed roadways (e.g., in a rural environment) change or transition to low-speed roadways (e.g., in an urban environment with higher development density, higher pedestrian activity, on-street parking, etc.). When entering a lower-speed zone, particularly after a period of driving at a high speed, drivers generally underestimate their speed and, consequently, do not reduce their speed sufficiently to comply with the lower speed limit. Infrastructure measures can help to indicate the transition from one traffic environment to another and help drivers adjust to the lower speed (*1*). In designing and selecting transition zone measures, the goal is to have motorists traveling at the lower speed at the start of the settled area, i.e., to have the speed reduction occur in the transition zone (*2*). Because physical measures are the most effective in reducing speed but are the most perilous if traversed at high speed, it may be helpful to recognize that an approach zone is required upstream of the transition zone to warn motorists. The transition zone and approach zone concept are shown in the figure below.

Design Guidelines

Transition Zone Areas	Recommended Measures
Rural Area with High Speed Limit	None
Approach Zone	Warning and psychological measures including advance signing, converging chevrons, optical speed bars, variable message signs, colored pavement, and transverse pavement markings.
Transition Zone	Physical measures including speed feedback signs, road narrowing, raised medians, stepped-down speed limit, roundabouts, and road diets.
Settled Area with Low Speed Limit	Gateway treatment at start of settled area and additional measures to manage speed within the settlement.

TRANSITION ZONE AND APPROACH ZONE CONCEPTS

Source: Forbes (*2*)

Discussion

A recently completed NCHRP Synthesis of Highway Practice (2) examined high-to-low speed transitions in North America and overseas. While the North American practice relies mainly on traffic signs, the experience from overseas is more varied and includes more extensive and aggressive measures such as geometric design changes, road surface treatments, and roadside features. The design guidance revealed in the literature review in this synthesis includes the following (*2*):

- More extensive and aggressive measures (e.g., mini roundabouts, raised speed tables) tended to produce greater reductions in speed and crash occurrence than less extensive and passive measures (e.g., gateway signing).
- There needs to be a distinct relationship between an urban speed limit and a change in the roadway character.
- There is not one particular measure that is appropriate for all situations. Each settlement must be assessed and treated based on its own characteristics and merits.
- To maintain a speed reduction downstream of the transition zone, it is necessary to provide additional measures through the village; otherwise, speeds may rebound to previous levels as soon as 820 ft from the start of the lower speed limit.

Distortions in speed estimation may be observed when a driver has to accelerate or decelerate. As a general rule, drivers usually produce a smaller change in speed than that required. The absolute error is greater after deceleration than after acceleration. This highlights the problems that drivers may face in the high-speed to low-speed transition area. Drivers make larger speed adjustments where the transitional situation is clearly functional (i.e., where the need to adjust the speed of their vehicle is sufficiently "obvious"). Signing alone is not sufficient to induce appropriate speed behavior if it does not correspond to the way in which the driver perceives and categorizes the situation. Discrepancies between the structural elements of the road environment and the posted speed reinforce inappropriate driving behavior (*1*).

Design Issues

Current AASHTO policy provides a sufficient level of detail for designing roads in a high-speed environment and a low-speed environment; however, the AASHTO Green Book (*3*) lacks sufficient guidance on the transition zones between the two facility types. NCHRP Project 15-40 "Design Guidance for High-Speed to Low-Speed Transition Zones for Rural Highways" is currently under way. The research will develop design guidance for selecting effective geometric, streetscaping, and traffic engineering techniques for transitioning from high-speed to low-speed roadways, particularity rural highways entering communities. The final report for NCHRP Project 15-40 will identify recommended changes to the Green Book to address design issues related to high- to low-speed transition zones. The project has developed a table of the effectiveness of transition zone techniques based on a literature review. The completion date of the project is scheduled for May 2012.

Speeds chosen are lower where the height of the vertical elements (e.g., trees, large shrubs, oversized signage; *4*) is greater than the width of the road. However, roadside elements need to be chosen carefully so as not to become obstacles which can have a negative effect on safety (*1*).

Cross References

Speed Perception, Speed Choice, and Speed Control, 17-1
Signing Guidelines, 18-1
Markings Guidelines, 20-1

Key References

1. Organization for Economic Co-operation and Development (OECD) and European Conference of Ministries of Transport (ECMT) (2006). *Speed Management.* Paris: OECD Publishing.
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CHAPTER 10

Non-Signalized Intersections

ACCEPTABLE GAP DISTANCE

Introduction

Acceptable gap distance refers to the size of the gaps in major-road traffic typically accepted by drivers turning from a minor road that provide sufficient time for the minor-road vehicle to accelerate from stop and complete a turn without unduly interfering with major-road traffic operations. A constant-value of time gap, independent of approach speed, can be used for determining intersection sight distance (see AASHTO (*1*)). In particular, the intersection sight distance in both directions should be equal to the distance traveled at the design speed of the major road during a period of time equal to the gap.

Design Guidelines

Design Vehicle	Time Gap (t_g) at Design Speed of Major Road	
	Left Turn	**Right Turn**
Passenger Car	7.5 s	6.5 s
Single-Unit Truck	9.5 s	8.5 s
Combination Truck	11.5 s	10.5 s

Note: Time gaps are for a stopped vehicle to turn onto a two-lane highway with no median and grades of 3% or less. The table values require adjustment as follows:

For multilane highways:

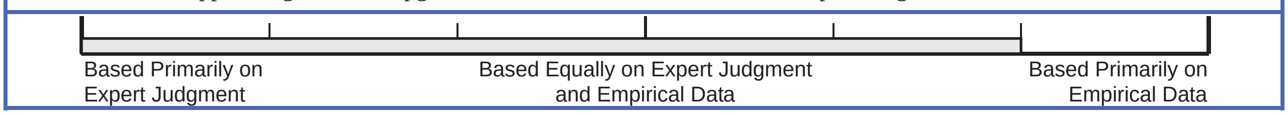
For turns onto highways with more than two lanes, add 0.5 s for passenger cars or 0.7 s for trucks for each additional lane (including narrow medians that cannot store the design vehicle), in excess of one, to be crossed by the turning vehicle.

For *left* turn onto minor roads with approach grades:

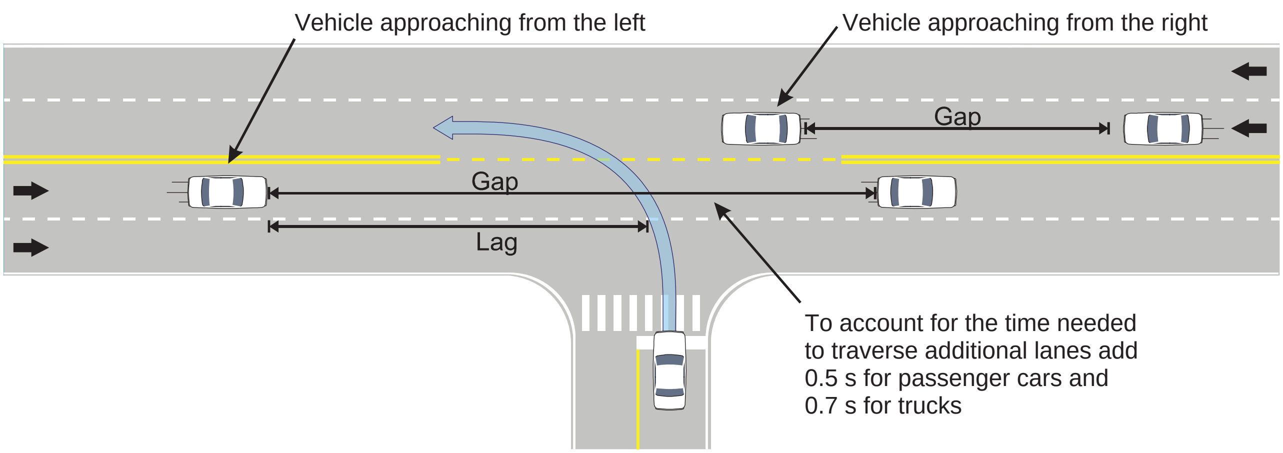
If the approach grade is an upgrade that exceeds 3%, add 0.2 s for each percent grade.

For *right* turn on minor roads with approach grades:

If the approach grade is an upgrade that exceeds 3%, add 0.1 s for each percent grade.



The figure below shows the different aspects of gap acceptance in a left-turn situation. Gaps are defined as the time interval between two successive vehicles, measured from the rear of a lead vehicle to the front of the following vehicle. Lags are defined as the time interval from the point of the observer to the arrival of the front of the next approaching vehicle.



Discussion

Safe gap acceptance distances depend on the driver's ability to accurately judge the time available to execute a traffic-crossing maneuver. Chovan, Tijerina, Everson, Pierowicz, and Hendricks (*2*) indicate that failure to accurately perceive and judge safe gap distances can have serious safety consequences, and that two of the most common causal factors for left turn crashes are misjudged gap/velocity (30% to 36% of crashes) and drivers misperceiving (e.g., "looked but did not see") oncoming traffic (23% to 26% of crashes).

At short distances, where the size of the visual image (on the observer's retina) of the oncoming traffic is relatively large, time-to-arrival judgments may be made based on optical properties of the scene, such as the observed rapid expansion ("looming") of the visual image as the object approaches (see, for example, Kiefer, Cassar, Flannagan, Jerome, and Palmer (*3*)). However, at the distances involved in roadway gap judgments there is less agreement about whether these optical properties are as important or if other aspects, such as speed and distance judgments, dominate. In general, however, observers are not particularly adept at making judgments about arrival time and they tend to underestimate this value by 20% to 40% (*4*). Fortunately, the degree of underestimation is reduced with higher oncoming vehicle speed and with longer viewing duration (*4*).

One study found that distance from oncoming vehicle was the best predictor of gap acceptance, while vehicle speed and time-to-arrival were weaker predictors (*5*). This finding suggests that drivers are somewhat insensitive to oncoming vehicle speed, which means that they may be more likely to accept smaller/less-safe gaps if the speeds of oncoming vehicles are higher. Also, this effect appears to be more pronounced in older drivers than in younger drivers (*6*).

The data for the acceptable gap distance guideline come from Harwood, Mason, and Brydia (*7*), which measured critical gap for use as an intersection sight distance criterion. For design purposes, the critical gap represents the gap between successive oncoming vehicles that average drivers will accept 50% of the time (and reject 50% of the time). The rationale for using critical gap as an ISD criterion is that if drivers will accept a specific critical gap in the major-road traffic stream when making a turning maneuver, then sufficient ISD should be provided to enable drivers to identify that critical gap. The key findings from Harwood et al. (*7*), which are reflected in the guideline, are that drivers accept slightly shorter gaps for right turns than for left turns, and that heavy vehicles require longer gaps. Note, however, that other studies have not found a difference in gap acceptance size based on turn direction. In particular, one study found that passenger vehicle drivers accepted a critical gap of 6.5 s for both left and right turns; this source also reviewed comparable studies that also found mixed results regarding the effect of turn direction (*8*). Another factor that must be considered is the direction from which drivers face conflicting traffic. In particular, Kittelson and Vandehey (*9*) found that left-turning drivers will accept shorter gaps if the gap they are evaluating involves a vehicle approaching from the left rather than from the right.

Design Issues

Vehicles approaching the turning/crossing vehicle can be expected to slow down to avoid any potential conflicts; however, this deceleration may impact capacity on high-volume roadways. Harwood et al. (*7*) found that for turns executed with gaps of less than 10 s, oncoming vehicles decelerated from 0% to 80% with a median deceleration of 31% (average deceleration level was 0.68 m/s^2). On average, two-thirds of the speed reduction occurs before the oncoming vehicle reaches the intersection. The average acceleration level of the turning vehicle was 1.46 m/s^2.

Cross References

Determining Intersection Sight Distance, 5-6
Factors Affecting Acceptable Gap, 10-4

Key References

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8. Fitzpatrick, K. (1991). Gaps accepted at stop-controlled intersections. *Transportation Research Record, 1303*, 103-112.
9. Kittelson, W.K., and Vandehey, M.A. (1991). Delay effects on driver gap acceptance characteristics at two-way stop-controlled intersections. *Transportation Research Record, 1320*, 154-159.

FACTORS AFFECTING ACCEPTABLE GAP

Introduction

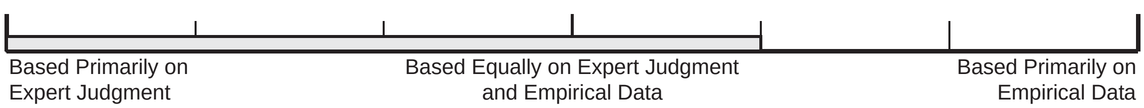
The *factors affecting acceptable gap* refer to the driver, environment, and other situational factors that cause most drivers or specific groups of drivers (e.g., older drivers) to accept smaller or larger gaps than they would otherwise accept under normal conditions. These guidelines only apply when there is no center median or acceleration lane that provides shelter to the turning vehicle.

Design Guidelines

Certain driver, environmental, or situational factors can systematically influence driver gap acceptance behavior. If these factors are common at an intersection location, then consideration should be given to modifying the gap acceptance design assumptions.

Factor	Finding	Data Quality*
Driver Age	Older drivers accept a critical gap that is approximately 1 s longer than younger drivers, and they reject more acceptable gaps overall.	●
Wait Times	Critical gap size decreases as a function of time spent waiting at the stop line.	●
Direction of Turn	Drivers will accept shorter gaps if the primary conflicting vehicle is approaching from the driver's left than if it is from the driver's right (same destination lane).	●
Familiarity with Roadway	Drivers on familiar routes (e.g., work commutes) accept smaller critical gaps.	○
Oncoming Vehicle Size	Larger vehicles are perceived as arriving sooner than smaller vehicles.	○
Traffic Volume	Drivers accept smaller gaps with higher major-road traffic volume.	○
Headlight Glare	Drivers accept longer critical gaps with oncoming headlight glare.	○

*Data Quality: ● = established finding; ○ = some empirical evidence, but magnitude of effect and reliability of findings are unconfirmed.



The table below shows the perceptual, cognitive, and psychomotor subtasks associated with the key activities that drivers must perform when making left or right turns across traffic in a four-lane roadway (adapted from Richard, Campbell, and Brown (9)).

Activity	Perceptual Subtasks	Cognitive Subtasks	Psychomotor Subtasks
1. Check for possible conflicts with following vehicle.	Visually assess trajectory of following vehicle.	Determine if distance and speed of vehicle indicate potential conflict.	Head and eye movements to observe rearview mirror.
2. Check for pedestrians/cyclists crossing or about to cross in front.	Look left and right along crosswalk.	Determine if pedestrians/cyclists are present or likely to enter the crosswalk.	Head and eye movements for viewing.
3. Advance into crosswalk.	Visually observe crosswalk.	Determine when vehicle is in appropriate position for turning.	Slowly accelerate and brake.
4. Look for gap in perpendicular traffic.	Visually monitor traffic.	Determine distance and speed of oncoming traffic. Determine if gap is sufficient for turning.	Head and eye movements to monitor oncoming traffic.
5. Check for oncoming vehicles in far lane changing to destination (conflicting) lane.	Monitor oncoming vehicles in far lane.	Determine if vehicle is about to change lanes (e.g., turn signal on, changing trajectory, etc.).	Head and eye movements to monitor oncoming traffic.
6. Check for hazards in turn path.	Visually scan turn path (especially crosswalk) and intended lane.	Determine if any pedestrians/cyclists or other hazards are in the crosswalk or about to enter.	Head and eye movements to view turn path.
7. Accelerate to initiate turn.	View roadway.	Determine that acceleration is sufficient to avoid conflicts with other vehicles	Quickly accelerate. Head and eye movements.
8. Steer into turn.	View turn path.	Determine that vehicle trajectory and lane position are appropriate.	Steering adjustments necessary to stay in lane.

Discussion

Driver age: Several studies have found that older drivers require gaps that are approximately 1 s longer than younger drivers. Some studies also find that older drivers tend to reject more usable gaps than other drivers, which leads to capacity reductions (*1*, *2*). The data suggest that these differences likely reflect more cautious decision criteria (*1*). Yi (*2*) also found that older drivers require more time to enter and accelerate to the desired speed (10–13 s to reach 25 mi/h and 16–19 s to reach 35 mi/h compared to the respective 7–9 s and 12–14 s for younger drivers).

Wait times: Most vehicles that wait in a queue accept smaller gaps than those that do not wait (*3*). Also, the longer that drivers wait, the more likely they are to accept gaps that they previously rejected as being too short (*4*). Note that there is no information about whether this arises from increased driver frustration or from drivers learning through observation that smaller gaps are likely to be safe (*3*).

Direction of turn: Drivers accept shorter gaps if the primary other vehicle is approaching from the driver's left than if it is approaching from the driver's right (*4*, *5*). For example, a driver making a left turn will accept a smaller gap from a vehicle approaching from the left (for which there will only be a conflict while the turning vehicle crosses its path), than one approaching from the right (for which there will be a potential conflict until the turning vehicle gets up to speed). If drivers are faced with a single vehicle coming in the conflicting direction, then some data suggest that drivers will accept shorter gaps while making right turns than left turns (*6*); however, there is also evidence that this difference is small or insignificant.

Familiarity with the roadway: Only one study considered the effects of driver familiarity on gap acceptance (*5*). This study found that drivers on regular commute trips generally accept smaller gaps, which seems to arise because drivers are familiar with what constitutes a safe gap in a particular turn situation.

Oncoming vehicle size: Some driving simulator research indicates that larger vehicles are perceived as arriving sooner than smaller vehicles, even if their actual arrival time is the same (*7*). This finding may have implications for roadways with high motorcycle traffic, because drivers may overestimate the gap size for these smaller vehicles.

Traffic volume: Higher traffic volume on the major road appears to lead to drivers accepting smaller gaps (*3*). This situation could arise because large gaps are less common or drivers see the need to take whatever gap is available, even if it is smaller than what they would normally take.

Headlamp glare: Data from a study involving unlit rural conditions indicated that accepted gaps were significantly larger under higher glare conditions from approaching vehicles, although the lighting systems used were from the late 1960s and therefore the data may be less applicable today (*8*).

Design Issues

None.

Cross References

Determining Intersection Sight Distance, 5-6
Acceptable Gap Distance, 10-2

Key References

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SIGHT DISTANCE AT LEFT-SKEWED INTERSECTIONS

Introduction

Sight distance at left-skewed intersections refers to the available sight distance to the driver's right side for a vehicle crossing a major road from a left-skewed minor road (where the acute angle is to the right of the vehicle). In left-skewed intersections, the driver's line of sight can be obstructed by parts of the driver's vehicle, such as the roof posts, door frame, passenger-seat headrest, or a panel aft of the door. This obstruction is most likely to occur for vehicles that have vision-restricting rearward elements, for example, ambulances, motor homes, truck tractors with sleeping areas, single-unit trucks, and school buses. These sight-line restrictions can result in reduced sight distances because the driver cannot see as far down the intersecting road as with 90° intersections. AASHTO (*1*) recommends that intersection angles be skewed no more than 60°; however, as Gattis and Low (*2*) indicate, intersections that are skewed from 60° to 70° can still result in insufficient sight distance for vision-restricted vehicles at certain design speeds.

The guideline provides information about available sight distance (ASD) and the design speed that accommodates the ASD for different viewing/vision angles. Two different vision angle conditions are presented. The minimum vision angle indicates design parameters for the minimum recommended vision angle. The desirable vision angle provides more conservative recommended values that better accommodate larger vehicles and older drivers.

Design Guidelines

Design speeds for the major roadway should be consistent with available sight distance for the minor-road vehicle based on at least the minimum vision angle viewing position, but use of the desirable vision angle is preferable and better accommodates larger vehicles and older drivers.

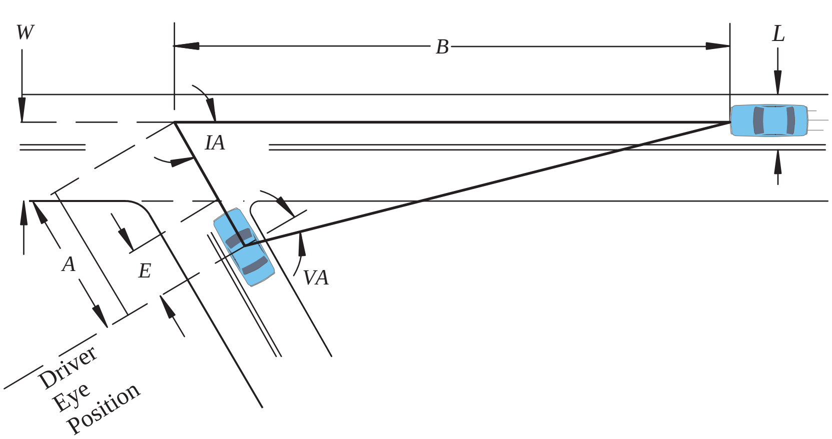
RESULTING AVAILABLE SIGHT DISTANCE FOR 5.4-M AND 4.4-M SETBACKS*

Intersection Angle (degrees)	Resulting ASD for a 5.4-m Setback				Resulting ASD for a 4.4-m Setback			
	Minimum Vision Angle: 13.5°		Desirable Vision Angle: 4.5°		Minimum Vision Angle: 13.5°		Desirable Vision Angle: 4.5°	
	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)
55	31.8	31	23.6	<30	–	–	–	–
60	39.8	37	26.9	<30	36.4	35	24.6	<30
65	55.4	46	32.3	32	50.5	43	29.5	30
70	95.7	65	41.6	38	87.1	61	37.8	36
75	408.2	>120	60.1	49	371.1	>120	54.6	46

**Calculations assume a W (see figure below) of 5.4 based on 1½ lane widths of 3.6 m.*

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

The figure below shows the variables and dimensions used to calculate the ASD and design speed values in the table.



A	Subject Vehicle (SV) Collision Distance
E	Setback Distance
B	Available Sight Distance
IA	Intersection Skew Angle
VA	Subject Vehicle Vision Angle
W	Distance from Principal Other Vehicle (POV) to Intersection Tangent Line
L	Lane Width (3.6 m)

Discussion

The available sight distances presented in the guideline are calculated based on drivers of restricted-vision vehicles viewing oncoming traffic backwards over their right shoulder. The 4.5° viewing-angle condition represents a driver sitting back fully against the seat, which represents the most restricted viewing-angle condition. Actual viewing angles from this position can range from around 2° in ambulances and motor homes to 7° or 8° in single-unit trucks and school buses. Viewing angles are typically more than 19° in all vehicles if drivers adopt an extreme "leaning forward" position in which their head is positioned almost directly above the steering wheel (*2*). The 13.5° viewing-angle condition used in the guideline represents an intermediate "leaning forward" driver posture that is between the "fully against the seat back" position and the "full forward" position. It was selected based on expert judgment of a review panel involved in the study and represents a reasonable approximation of how far forward most drivers could be expected to lean.

Son, Kim, and Lee (*3*) measured the available vision angle in three Korean design vehicles (passenger cars, single-unit trucks, and semi-trailers). The viewing angles in single-unit trucks and semi-trailers were 1.3° in the "seat back" position and 12.6° to 13.1° in the "full forward" position. However, viewing angles from a comfortable "leaning forward" position in these vehicles were 5.2° to 5.4°, which are smaller than the 13.5° viewing angle adopted for the guideline. Viewing angles for passenger cars were much greater, having values of 13.5° and 17° in the "seat back" and comfortable "leaning forward" positions, respectively.

It should be noted that some drivers, especially older drivers, may be restricted in their ability to lean forward because of limitations in their neck and trunk flexibility, and therefore the intermediate "leaning forward" position (13.5°) may be difficult to obtain. If the design must accommodate older drivers, use of the desirable vision angle may be more appropriate. See the guideline "Sight Distance at Right-Skewed Intersections" for additional discussion of this issue.

The design speed measure reported in the guideline is based on the time available for the vehicle on the major road to stop or avoid a conflict with the minor-road vehicle that entered the intersection late based on what its driver could see from the restricted viewing angle. Note that vehicles passing through skewed intersections also have a longer distance to traverse, which increases the driver's exposure to oncoming traffic.

The 5.4-m setback represents a conservative estimate for how far back the driver's eye position is from the edge of the major road. More specifically, it is based on the distance of 5.4 m measured from the minor-road vehicle driver's eye to the edge of the cross road. This value is the recommended driver-position setback for intersection sight distance calculations (*4*). However, a setback distance of 4.4 m may also be used for constrained situations and is consistent with driver behavior in response to restricted sightline situations.

Design Issues

To what extent the current recommendations apply to light trucks is uncertain at this point. Restricted rearward viewing may occur with light trucks because some lack a rear seating area with windows and some have truck bed attachments that can obscure the rearward view.

Cross References

Determining Intersection Sight Distance, 5-6
Sight Distance at Right-Skewed Intersections, 10-8

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
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SIGHT DISTANCE AT RIGHT-SKEWED INTERSECTIONS

Introduction

Sight distance at right-skewed intersections refers to the available sight distance to the driver's left side for a vehicle crossing a major road from a right-skewed minor road (where the acute angle is to the left of the vehicle). In right-skewed intersections, the drivers' line of sight over their left shoulder is not typically obstructed by parts of their vehicle, such as the case with left-skewed intersections. In contrast, the primary limitations to drivers' line of sight are their ability to physically turn their body to the left and how far over their shoulder they can orient their gaze to view oncoming vehicles. These viewing limitations can result in reduced sight distances because the driver can not see as far down the intersecting road as they could at a 90° intersection. The guideline provides recommendations for accommodating older drivers who are more likely to have neck and/or trunk movement restrictions, in addition to recommendations for drivers without such limitations (identified as "other drivers").

Design Guidelines

Design speeds for the major roadway should be consistent with available sight distance (ASD) for the minor-road vehicle based on at least the vision angle for drivers without neck and/or trunk movement restrictions (other-driver); however, the use of the older-driver vision angle better accommodates older drivers and those drivers with neck and/or trunk movement restrictions regardless of age.

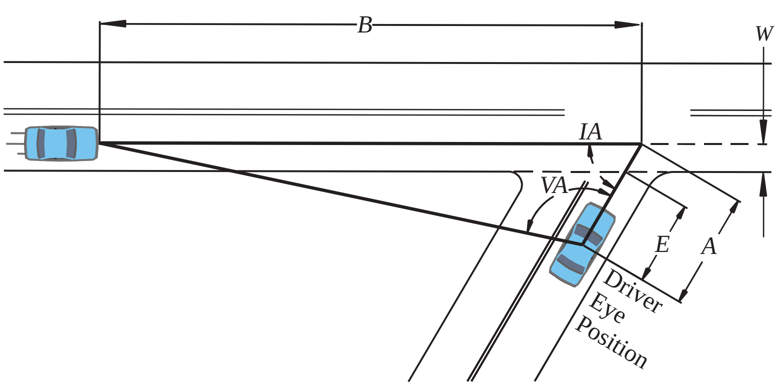
RESULTING AVAILABLE SIGHT DISTANCE FOR 5.4-M AND 4.4-M SETBACKS*

Intersection Angle (degrees)	Resulting ASD for a 5.4-m Setback				Resulting ASD for a 4.4-m Setback			
	Other-Driver Vision Angle: 115°		Older-Driver Vision Angle: 95°		Other-Driver Vision Angle: 115°		Older-Driver Vision Angle: 95°	
	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)
55	39.7	35.8	15.1	17.0	35.0	32.7	13.3	15.3
60	77.8	57.4	17.6	19.2	68.4	52.7	15.5	17.3
65	Not limited†	>120	21.5	22.6	Not limited†	>120	18.9	20.3
70	Not limited†	>120	28.2	27.8	Not limited†	>120	24.7	25.1
75	Not limited†	>120	41.7	37.2	Not limited†	>120	36.5	33.7

**Calculations assume a W (see figure below) of 1.8 based on ½ a lane width of 3.6 m.*

†At higher intersection angles, driver visibility is not limited by vision angle.

The figure below shows the variables and dimensions used to calculate the ASD and design speed values used in the guideline table.



A	Subject Vehicle (SV) Collision Distance
E	Setback Distance
B	Available Sight Distance
IA	Intersection Skew Angle
VA	Subject Vehicle Vision Angle
W	Distance from Principal Other Vehicle (POV) to Intersection Tangent Line

Discussion

The primary limiting factor for visibility with right-skewed intersections is the drivers' direct field of view based on how far over their left shoulder they can see by turning their body, head, and eyes to the left. This visibility limitation contrasts with left-skewed intersections, in which parts of the vehicle body can obstruct the drivers' view over their right shoulder regardless of how far they can see to the side. Difficulty with head turning was one of the most frequently mentioned concerns in older-driver focus groups, and these drivers reported experiencing difficulty turning their heads at angles less than 90° to view traffic on intersecting roadways. Moreover, joint flexibility declines by an estimated 25% in older drivers because of arthritis, calcification of cartilage, and joint deterioration (*1*). If roadway designers need to consider older-driver capabilities in the design of skewed intersections, then use of the older-driver vision angle values from the guideline is recommended.

The values in the guideline table provide estimated ASD and recommended design speed for oncoming vehicles based on approximations of how far to the left drivers on the minor road can be expected to see. The ASD and design speed values in the guideline table were computed using an analogous approach to the one taken in the guideline "Sight Distance at Left-Skewed Intersections," which is based on Gattis and Low (*5*). Specifically, these terms represent the time available for a vehicle on the major road to stop or avoid a conflict with the minor-road vehicle that entered the intersection based on what its driver could see from the restricted viewing angle.

The minor-road driver's viewing angle is calculated using estimated trunk, head, and eye movement capabilities observed in healthy young and middle-aged drivers (other-driver vision angle) and healthy older drivers (older-driver vision angle). For the other-driver vision angle, trunk, neck, and eye movement values of 30°, 70°, and 15° (totaling 115°) were used. For the older-driver vision angle, trunk, neck, and eye movement values of 25°, 55°, and 15° (totaling 95°) were used.

No data are currently available on trunk rotation range for seated drivers restrained by safety belts. The trunk rotation value used in the guideline calculations was based on an estimate of comfortable trunk rotation range for a restrained non-older driver of 30°, and then reduced by 5° to represent reduced flexibility in older drivers.

The neck rotation values are based on the study by Isler, Parsonson, and Hansson (*2*), which measured neck rotation to the left in seated drivers. In this study, 80% of drivers aged 59 years or younger had a neck movement range of 70° or more, while 75% of drivers aged 60 or older had a neck movement range of 55° or more. Note that these values are greater than those reported in another more comprehensive study of neck rotation, which found *mean* neck rotation to the left to be 65° in healthy people aged 20 to 59, and 54° in healthy people aged 60 to 79 (*3*).

The guideline table also assumes that drivers are able to execute at least one eye movement 15° toward the left. There are no data indicating how far drivers will move their eyes when making judgments about oncoming vehicle approaches; however, most naturally occurring eye movements (saccades) have an amplitude of 15° or less, and eye movements longer than this are effortful (*4*). While this 15° value may be considered as representing a conservative eye movement amplitude, many older drivers have limited peripheral vision, which would make it difficult to efficiently move their eyes farther out than 15° (*2*).

Design Issues

The estimates of how far drivers can see to their left contain some degree of uncertainty, because of the lack of reliable information on driver trunk rotation and eye movement amplitude.

Cross References

Determining Intersection Sight Distance, 5-6
Sight Distance at Left-Skewed Intersections, 10-6

Key References

1. Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001). *Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians.a* (FHWA-RD-01-051). McLean, VA: FHWA, Research, Office of Safety R&D.
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4. Bahill, A.T., Adler, D., and Stark, L. (1975). Most naturally occurring human saccades have magnitudes of 15 degrees or less. *Investigative Ophthalmology, 14*(6), 468-469.
5. Gattis, J.L. and Low, S.T. (1998). Intersection Angle Geometry and the Driver's Field of View. *Transportation Research Record, 1612*, 10-16.

COUNTERMEASURES FOR IMPROVING ACCESSIBILITY FOR VISION-IMPAIRED PEDESTRIANS AT ROUNDABOUTS

Introduction

This guideline identifies *countermeasures for improving accessibility for vision-impaired pedestrians at roundabouts*. Title II of the Americans with Disabilities Act (ADA) requires that new and altered facilities constructed by, on behalf of, or for the use of state and local government entities be designed to be readily accessible to and usable by people with disabilities (28 CFR 35.151). Also, FHWA states that "a visually impaired pedestrian with good travel skills must be able to arrive at an unfamiliar intersection and cross it with pre-existing skills and without special, intersection-specific training" (*1*).

Roundabouts can be particularly challenging to navigate for vision-impaired pedestrians. In particular, vision-impaired pedestrians typically wait much longer to cross at roundabouts than sighted pedestrians, especially if traffic volume is high. One reason that sighted pedestrians have shorter wait times is that they can accept gaps that are initially too short but can be extended by driver yields and they can use eye gazes and manual gestures to communicate with drivers and get confirmation of driver yielding. Because vision-impaired pedestrians cannot communicate in this manner, they are forced to wait for what they deem to be sufficient gaps based on sound information. Another problem is that vision-impaired pedestrians rely heavily on sound cues to get a sense of what vehicles are doing. The continuous traffic flow within the circle can eliminate important sound cues about vehicle movements, in addition to masking sound cues from vehicles approaching the roundabout. Anecdotally, vision-impaired pedestrians typically state they would most likely avoid roundabouts if getting sufficient information about vehicle movements is too difficult.

Design Guidelines

COUNTERMEASURES FOR IMPROVINGACCESSIBILITY FOR VISION-IMPAIRED PEDESTRIANS AT ROUNDABOUTS

Countermeasure	Applicable Situation	Effectiveness
Rumble/sound strips	Two-lane roundabouts	Poor
Rumble/sound strips	One-lane roundabouts	Unknown
Pedestrian-actualized traffic signals at midblock	One or two-lane roundabouts	Good*
Splitter island	One or two-lane roundabouts	Poor
Yield signs	One or two-lane roundabouts	Poor
Advanced vehicle detection technologies	One or two-lane roundabouts	Unknown

*Simulation results only. This countermeasure has not yet been field tested.

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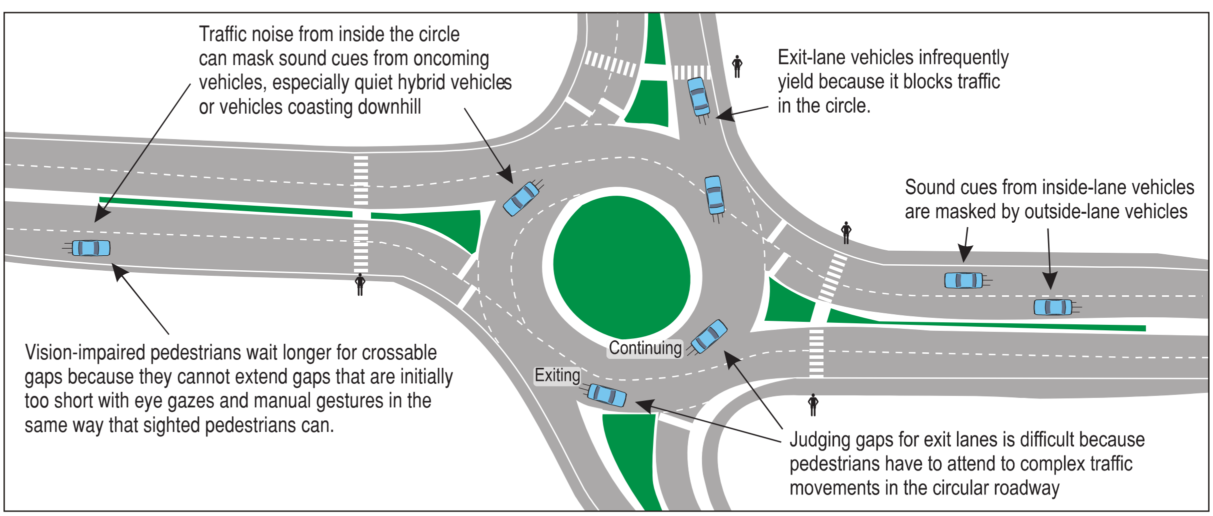
The figure below illustrates some of the roundabout elements that cause navigation difficulties for vision-impaired pedestrians.



Discussion

Rumble/sound strips: One study (*2*) that looked at sound strips in two-lane roundabouts found that they increased the chance that a vision-impaired pedestrian would detect a stopping vehicle and also decreased the time needed to make the detection by more than 1 s. However, sound strips did not reduce false alarm rates, and the observed level of 13% false alarms makes this countermeasure unacceptable for deployment. One problem was that detecting a second stopping vehicle was particularly difficult if that vehicle was in the far lane because its sound was masked by the vehicle in the near lane. Participants in this study were not trained to use the sound cues provided by the pavement treatment, nor were they informed of the treatment before the debriefing. It is conceivable that with training, detection performance with the sound strips would have been better, and false alarms might have been reduced. However, the majority of vehicles stopped before reaching the sound strips and did not produce the intended sound, which may reduce the effectiveness of any training.

This same study found that detection of stopping vehicles was relatively high when only one lane of traffic had to be monitored at a time (80% to 90% correct), which suggests that a sound-strip pavement treatment may be effective in single-lane roundabouts. However, any benefits of sound strips would likely be diminished if drivers consistently stop before reaching the sound strips, as mentioned previously.

Pedestrian-actualized traffic signals at midblock: An analysis of pedestrian crossing treatments indicated that midblock signals appear to be a useful compromise between increasing safety/quality of service and reducing vehicle capacity (*3*). In particular, they appear to be effective in eliminating queues that back up into the intersection under most conditions. Midblock crosswalks also have the advantage of being farther away from the intersection traffic, which makes it easier for vision-impaired pedestrians to determine what is happening because there is less masking noise from traffic within the circle. Note, however, that these results are based on simulation research, and the results have not been studied empirically.

Splitter islands: These features pose special challenges to vision-impaired pedestrians and are still associated with gap judgment difficulties. For example, one study found that vision-impaired participants (1) were nearly 2.5 times *less* likely to make correct judgments than sighted participants, (2) took longer to detect crossable gaps, and (3) were more likely to miss crossable gaps altogether (*4*). However, these differences were only significant at higher volume roundabouts. Overall, judging gaps in the exit lane is particularly difficult for vision-impaired pedestrians because they have to attend to vehicles in the exit lane and the circulatory roadway. This difficulty is compounded by drivers infrequently yielding in the exit lanes, typically because such yielding tends to back up traffic in the roundabout.

Yield signs: Vision-impaired pedestrians typically failed to detect when drivers had yielded for them, which suggests that efforts to encourage driver yielding may be of limited use (*5*).

Design Issues

Because most vision-impaired and low-vision pedestrians rely primarily on sound cues to determine traffic conditions, quiet oncoming vehicles pose a potential hazard. In particular, hybrid vehicles operating in battery-powered mode and vehicles that coast downhill towards a roundabout can be difficult to hear above other traffic noise. In this case, providing sound strips or other measures that make these vehicles easier to hear may assist vision-impaired or low-vision pedestrians in detecting oncoming vehicles.

Cross References

Countermeasures for Improving Accessibility for Vision-Impaired Pedestrians at Signalized Intersections, 11-8

Key References

1. FHWA (2000). *Roundabouts: An Informational Guide* (Publication FHWA-RD-00-067). Washington, DC.
2. 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.* Washington DC: FHWA.
3. Rouphail, N., Hughes, R., and Chae, K. (2005). Exploratory simulation of pedestrian crossings at roundabouts. *Journal of Transportation Engineering, 131*(3), 211-218.
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5. Ashmead, D.H., Guth, D., Wall, R.S, Long, R.G., and Ponchillia, P.E. (2005). Street crossing by sighted and blind pedestrians at a modern roundabout. *Journal of Transportation Engineering, 131*(11), 812-821.

CHAPTER 11

Signalized Intersections

ENGINEERING COUNTERMEASURES TO REDUCE RED LIGHT RUNNING

Introduction

Red light running refers to drivers' entering a signalized intersection when a red light is being presented (*1*). Several engineering countermeasures to reduce red light running have been proposed in McGee, Eccles, Clark, Prothe, and O'Connell (*1*) and Bonneson and Zimmerman (*2*). Some of these countermeasures reflect expert judgment, but most are supported by empirical research.

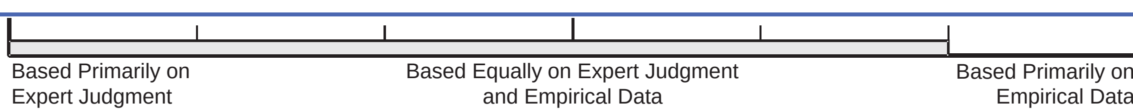
Importantly, Bonneson and Zimmerman (*2*) note the number of driver-, intersection-, vehicle-, and environment-related factors that are correlated with red light violation frequency and likelihood. These factors include traffic volume, cycle length, advance detection for green extension, speed, signal coordination, approach grade, yellow interval duration, proximity to other vehicles, presence of heavy vehicles, intersection width, and signal visibility.

Design Guidelines

The following engineering countermeasures address red light running at signalized intersections.

Countermeasure Type	Engineering Countermeasure
Traffic Characteristics, Operation, or Geometry	• Reduce approach speed by 5 mi/h • Reduce delay through retiming if volume-to-capacity (v/c) ratio > 0.70 • Reduce unnecessary delay through signal retiming • Improve signal coordination (goal is lower delays and longer cycle lengths) • Remove unneeded signals • Add capacity with additional lanes or turn bays
Signal Operation	• Increase signal cycle length by 10 s if v/c ratio < 0.60 • Provide green extension (advance detection) • Add protected-only left-turn phasing
Motorist Information	• Improve signal visibility via better signal head location • Improve signal visibility via additional signal head • Improve signal visibility by clearing sight lines to signal • Improve signal conspicuity by upgrading to 12-in. lenses • Improve signal conspicuity by using yellow LEDs • Improve signal conspicuity by using red LEDs • Improve signal conspicuity by using back plates • Improve signal conspicuity by using dual red indications • Add advance warning signs (can be with or without active flashers) • Add red light enforcement cameras

Source: Adapted from Bonneson and Zimmerman (*2*)



Discussion

Several driver-related factors and driver behaviors are relevant to red light running and countermeasure selection. Campbell, Smith, and Najm (*3*) report on a study that examined fatal crashes from 1999 and 2000 included in the Fatal Accident Reporting System (FARS) and found that, of the 9,951 vehicles involved at fatal signalized-intersection crashes, 20% failed to obey the traffic signal and 13% failed to yield the right-of-way; contributing factors included alcohol, speeding, and racing. Porter and Berry (*4*) note that in a survey that assessed red-light-running perceptions of 880 licensed drivers, the only factor that predicted recent red light running was age group—younger respondents were more likely to run red lights. In Retting and Williams (*5*), video data collected by an automated camera were analyzed to identify key characteristics of red light running. The authors found that, as a group, red light runners were younger, were less likely to be wearing seat belts, and had more convictions for moving violations. McGee et al. (*1*) summarizes the red-light-running problem, as well as a number of engineering countermeasures, and notes that driver-related factors associated with red light running include driver expectancies, driver knowledge of the intersection and the traffic signal (e.g., the yellow interval), and the driver's estimate of the consequences of not stopping (e.g., threat of a right-angle crash or a citation) versus stopping (e.g., threat of a rear-end crash or delays).

In Bonneson and Zimmerman (*2*), an integrative review of past analyses and research was conducted to identify engineering countermeasures having promise for reducing the number of red light violations at intersections and/or the number of crashes associated with red light violations. The engineering countermeasures presented on the opposing page have been adapted from Bonneson and Zimmerman (*2*), but are also presented in slightly different formats in McGee et al. (*1*) and Bonneson, Zimmerman, and Brewer (*6*).

Design Issues

McGee et al. (*1*) make an important distinction between intentional and unintentional red light running that can affect countermeasure selection and development. Specifically, McGee et al. (*1*) note that *intentional* red light runners are most affected by enforcement countermeasures (such as red light cameras) while *unintentional* red light runners are most affected by engineering countermeasures.

Red light cameras are frequently employed as enforcement countermeasures to reduce red light running. In Council, Persaud, Eccles, Lyon, and Griffith (*7*), an empirical Bayes before/after approach was used to determine effectiveness of red light cameras at 132 treatment sites. The authors report that red light cameras were associated with decreased right-angle crashes and increased rear-end crashes, with an aggregate crash cost-benefit associated with the use of red light cameras. Also, the presence of warning signs at both the city limit and the intersection was associated with a larger benefit than signs at just the intersection; high publicity was also associated with higher benefits. Caveats associated with the study were that other variables (driver, traffic volumes, temporal, environmental, signal) were either not included in the analyses (uncontrolled or confounded) or not associated with a large enough sample to detect an effect. Also, the analyses could not distinguish the effects of other improvements occurring at the same location as the red light cameras.

Cross References

Heuristics for Selecting the Yellow Timing Interval, 11-6

Key References

1. McGee, H., Eccles, K., Clark, J., Prothe, L., and O'Connell, C. (2003). *Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running.* Washington, DC: ITE.
2. Bonneson, J., and Zimmerman, K. (2004). *Red-Light-Running Handbook: An Engineer's Guide to Reducing Red-Light-Related Crashes*. College Station: Texas Transportation Institute.
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7. Council, F.M., Persaud B., Eccles, K., Lyon, C., and Griffith, M.S. (2005). *Safety Evaluation of Red-Light Cameras*. (FHWA-HRT-05-048). McLean, VA: FHWA.

RESTRICTING RIGHT TURNS ON RED TO ADDRESS PEDESTRIAN SAFETY

Introduction

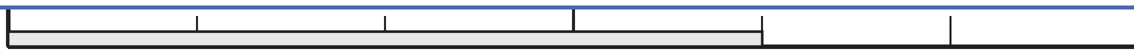
This guideline describes approaches for implementing restrictions on right turn on red (RTOR) movements with the objective of reducing conflicts between pedestrians and right-turning vehicles. The MUTCD (*1*) provides six situations where RTOR should be restricted, and three of these specifically address pedestrians: (1) where an exclusive pedestrian phase exists, (2) where significant pedestrian conflicts result from RTORs, and (3) where there is significant crossing activity by pedestrians who are children, are elderly, or have disabilities.

Typically, around 40% of drivers do not stop completely before making a RTOR (*2*). Of those drivers that do stop, many will stop beyond the marked stop line and block the pedestrian crosswalk while waiting to turn. This blocking of the crosswalk can impede pedestrian movements or cause pedestrians to walk outside of the marked crosswalk. Also, pedestrians may yield the right-of-way before entering the intersection and may not have time to clear the intersection before the signal changes. This is especially problematic for older pedestrians who take longer to cross.

Design Guidelines

Restrictions on RTOR can be used to reduce conflicts between pedestrians and turning vehicles, and to increase the likelihood that drivers will stop before turning right at an intersection.

- The most effective method is to base turning restrictions on time of day (e.g., from 6:00 am to 6:00 pm).
- Basing restrictions on the presence of pedestrians at the intersection will also reduce conflicts; however, this approach appears to be significantly less effective than time-based restrictions.



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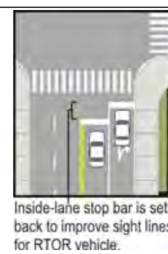
The table below shows examples of different implementations for RTOR signage.

Countermeasure Example				
Effectiveness	Most effective	Effective with low to moderate volume of RTOR	Effective when sight distances are problematic	Effective

Countermeasure	Key Features	Preferred Application
Red Ball on NTOR Sign	More "eye catching"	This is an effective signing approach in most situations.
Larger 30″ x 36″ Size	More conspicuous	On the far side of a wide intersection.
"When Pedestrians are Present" Addition	Permits RTOR but requires drivers to yield to pedestrians	Sites with low to moderate volumes of RTOR and pedestrian volumes that are low or occur primarily during intermittent periods.
Offset Stop Bar	Provides improved sight distance to RTOR vehicle	Sites with two or more approach lanes, heavy truck or bus traffic, or unusual geometries.
Variable Blank-Out Signs	Lit only during times that RTOR is prohibited	When pedestrian protection is critical during certain time periods (e.g., in school zones) or during a signal cycle when a separate, opposing left-turn phase may conflict with an unsuspecting RTOR driver.
"Look for Turning Vehicles" Pavement Markings	Can make pedestrians more cautious	Sites with particular problems involving pedestrian crashes or conflicts with RTOR vehicles.

Discussion

With regard to conditional RTOR restrictions, restrictions based on certain times of day (time-restricted) and those based on the presence of pedestrians (pedestrian-restricted) increase drivers' stopping at the stop line (*3*). However, the time-restricted implementation appears to be more effective both when pedestrians are present and when they are not. Retting, Nitzburg, Farmer, and Knoblauch (*3*) found that the pedestrian-restricted implementation significantly reduced RTOR when pedestrians were present (by 11%), but they still occurred 57% of the time. In contrast, time-restricted implementation led to a much greater reduction (from 77% to 19%). Additionally, the time-restricted implementation significantly increased the number of drivers that stopped before making a RTOR, while the pedestrian-restricted implementation did not. There was also a difference in terms of pedestrian capacity. In particular, the time-restricted implementation significantly reduced the number of pedestrians that yielded to drivers, but the pedestrian-restricted implementation did not.

Time-restricted implementations can be based on when pedestrian–turning vehicle crashes are most likely to occur. In particular, Stutts, Hunter, and Pein (*4*) found that 80% of intersection crashes involving pedestrians and turning vehicles occur between 6:00 am and 6:00 pm.

Regarding the relative effectiveness of different signage options, Zeger and Cynecki (*5*) compared different approaches and found that the NO TURN ON RED (NTOR) sign with a red ball was more effective than the standard black and white NTOR sign. Also, NO TURN ON RED WHEN PEDESTRIANS ARE PRESENT signs were effective at sites with moderate to low volumes of RTOR vehicles, although the legend was found to be difficult to read when located adjacent to the signal or on the far side of the intersection. Lastly, the presence of an offset stop bar improved motorist compliance, reduced conflicts with cross-street traffic, and was recommended for use on multilane approaches under some conditions (see Zeger and Cynecki (*5*)).

Another issue to consider is the use of electronic signing, such as blank-out NTOR signs that are lit only during the times that turns are restricted. In Zeger and Cynecki (*5*), an electronic NTOR blank-out sign was slightly more effective, although considerably more costly, than traditional signs. Similarly, another study found that sites with variable message signs were effective in lowering incidence of motorists who illegally turned right on red. This study did not compare the effectiveness to traditional signs, so it is unclear if the benefits outweighed the additional costs of the variable message signs.

Design Issues

Several factors can diminish the effectiveness of RTOR restrictions on driver compliance (see Zeger and Zeger (*6*)):

- Confusing partial prohibitions (e.g., 7-9 am and 4-6 pm, except Sundays)
- Far-side or hidden NTOR signs
- Long cycle lengths
- Confusing multi-leg intersections
- NTOR that does not appear to be justified given the traffic conditions

Also, inconsistent placement of RTOR signs from intersection to intersection can reduce the effectiveness of the signs.

Cross References

Determining Intersection Sight Distance, 5-6
Sight Distance at Right-Skewed Intersections, 10-8

Key References

1. FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
2. ITE (1992). Driver behavior at right-turn-on-red locations. *ITE Journal, 62*(4), 18-20.
3. Retting, R.A., Nitzburg, M.S., Farmer, C.M., and Knoblauch, R.L. (2002). Field evaluation of two methods for restricting right turn on red to promote pedestrian safety. *ITE Journal, 72*(1), 32-36.
4. Stutts, J.C., Hunter, W.W., and Pein, W.E. (1996). Pedestrian-vehicle crash type: An update. *Transportation Research Record, 1538*, 68-74.
5. Zegeer, C.V., and Cynecki, M.J. (1986). Evaluation of countermeasures related to RTOR accidents that involve pedestrians. *Transportation Research Record, 1059*, 24-34.
6. Zegeer, C.V., and Zegeer, S.F. (1988). *NCHRP Synthesis of Highway Practice 139: Pedestrians and Traffic-Control Measures*. Washington, DC: Transportation Research Board.

HEURISTICS FOR SELECTING THE YELLOW TIMING INTERVAL

Introduction

The *yellow timing interval* refers to the duration of the yellow signal indication; the yellow timing interval is also referred to as the "yellow change interval" in a number of sources. The yellow signal warns oncoming traffic of an imminent change in the right-of-way assignment (*1*,*2*). Most traffic engineering sources (*1*,*2*,*3*) recommend a yellow change interval of 3 to 5 s duration. Increases to a given yellow timing interval are usually implemented in order to decrease instances of red light running. Van Winkle (*4*) notes that the many variables influencing the selection of yellow timing intervals include approach speed, intersection width, vehicle length, vehicle deceleration level, visibility of traffic signals, response time of the driver, degree of enforcement, specific laws, and motorist attitudes; this source also recommends using a consistent interval to eliminate driver uncertainty as a variable.

Design Guidelines

Pline (*1*) and ITE Technical Council Committee 4TF-1 (*5*) indicate that the following formula can be used to calculate the yellow timing interval time plus the red clearance interval time.

Metric Values [English Values]

$$CP = t + \frac{V}{2a + 2Gg} + \frac{W + L}{V}$$

Metric:

- a = deceleration, m/s^2 (typically 3.1 m/s^2)
- G = gravity @ 9.8

English:

- a = deceleration, ft/s^2 (typically 10 ft/s^2)
- G = gravity @ 32.2

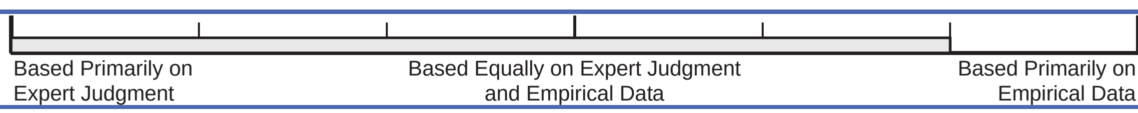
Where:

- CP = non-dilemma change period (Change + Clearance Intervals)
- t = perception-reaction time (nominally 1 s)
- V = approach speed, m/s [ft/s]
- g = percent grade (positive for upgrade, negative for downgrade)
- a = deceleration, m/s^2 (typical 3.1 m/s^2) [ft/s^2 (typical 10 ft/s^2)]
- W = width of intersection, curb to curb, m [ft]
- L = length of vehicle, (typical 6 m) [ft (typical 20 ft)]

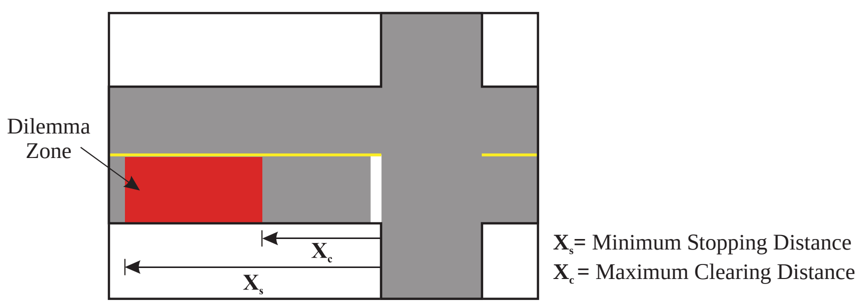
From Pline (*1*):

- Yellow timing intervals should generally have a duration of 3 to 5 s. If more than 5 s is required, a red clearance interval is used.
- Because a longer interval may encourage drivers to use the yellow as a part of the green interval, a maximum of about 5 s for the yellow timing interval is generally used.
- When the calculation for the yellow timing interval yields a time greater than 5 s, a red clearance interval generally provides the additional time.
- Given the many variables included in the formula above (estimates for reaction time, vehicle deceleration, grades, and intersection clearing time), engineering judgment should be used to apply the results of these calculations toward determining the yellow change interval.

FHWA (*2*) notes that the yellow timing interval "may be followed by an optional red clearance interval to provide additional time before conflicting traffic movements, including pedestrians, are released"; it further notes that this all-red interval should not exceed 6 s.



The figure below depicts the dilemma zone when a driver approaching a signalized intersection is faced with a green light that changes to yellow (adapted from Pant, Cheng, Rajaopal, and Kashayi (*8*)).



Discussion

Driver behaviors relevant to the selection of a yellow timing interval have been studied by the transportation research community for many years. Tijerina, Chovan, Pierowicz, and Hendricks (*6*) note that crash data for signalized intersections show that the decision to proceed through a yellow signal likely represents a source of problems for many drivers.In particular, the most common contributing factors include deliberately running the signal (40%), either because drivers failed to obey the signal (23.1%) or tried to beat the signal (16.2%). The next most common contributing factor was driver inattention (36.4%). A critical aspect of driver behavior related to the yellow timing interval is associated with the "dilemma zone." When a driver sees a green signal changing to yellow, a dilemma zone is created. The dilemma zone represents the portion of the roadway between (1) the clearing distance to the intersection (the distance the vehicle travels between the time the signal changes to yellow to the time the signal changes to red) and (2) the stopping distance (the distance traveled by the vehicle between the time the signal changes to yellow to the time when the vehicle actually stops) when the stopping distance is greater than the clearing distance. The dilemma zone is therefore not a fixed area. While in the dilemma zone, the driver must assess the situation and then decide whether to stop or proceed through the intersection based on that assessment.

A recent task analysis of driver behavior while traveling straight through an intersection on a yellow signal (*7*) confirms that the decision to stop or not is a complex one. As noted in Richard, Campbell, and Brown (*7*), there are two reasons drivers run the signal (and risk a right-angle crash) when the appropriate action would be to stop: (1) they correctly assess the situation as unsafe and then make a bad decision to go anyway, or (2) they incorrectly assess the situation as safe (perhaps because the driver missed relevant information) and make the logical—but incorrect—decision to proceed. The latter case is similar to driver inattention, whereby drivers also fail to adequately perceive and process the necessary situational information. Overall, it is clear that dilemma zone situations provide limited options for drivers not only because they have an extremely limited amount of time to perform several tasks, but also because they are limited in the types of actions they can safely or legally take.

Pant et al. (*8*) carried out a study to test and implement a dilemma zone protection technique (placement of detectors leading up to the intersection and the use of a green extension of 1 to 5 s) at three high-speed intersections in Ohio. The authors report that the use of detectors, combined with a 3-s extension, can provide drivers with some dilemma zone protection. They also note that differences among intersections with respect to vehicle speeds, operational characteristics, and geometries suggest that specific solutions are unique to individual intersections.

Design Issues

The possibility of long-term driver adaptation to longer yellow timing intervals has not been extensively studied. Specifically, the driver behavior and crash rates associated with changes in the yellow timing interval seen in many of the field studies in this area may reflect only temporary effects that will recede once drivers acclimate to the longer yellow.

Cross References

Engineering Countermeasures to Reduce Red Light Running, 11-2

Key References

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COUNTERMEASURES FOR IMPROVING ACCESSIBILITY FOR VISION-IMPAIRED PEDESTRIANS AT SIGNALIZED INTERSECTIONS

Introduction

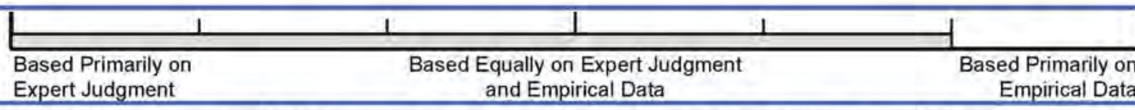
This guideline identifies accessible pedestrian signals (APSs) and curb treatment recommendations for improving accessibility for vision-impaired pedestrians at signalized intersections. Title II of ADA requires that new and altered facilities constructed by, on behalf of, or for the use of state and local government entities be designed to be readily accessible to and usable by people with disabilities (28 CFR 35.151). Unfamiliar signalized intersections can pose several challenges that reduce accessibility and safety for vision-impaired or low-vision pedestrians who use signalized intersections while traveling on their own (*1*).

Design Guidelines

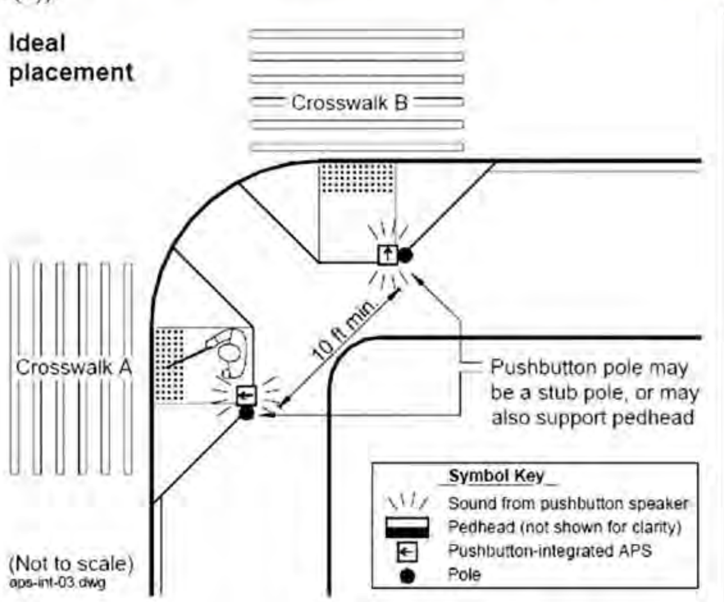
COUNTERMEASURES FOR IMPROVING ACCESSIBILITY AT SIGNALIZED INTERSECTIONS

Recommendation	Rationale
Avoid using large-radius corners and curb ramps aligned at various angles.	These corners and ramps make it more difficult for vision-impaired pedestrians to align themselves with the crosswalk.
Use domed curb-ramp surfaces instead of rough aggregate surfaces.	A majority of vision-impaired pedestrians fail to detect rough aggregate surfaces.
Lengthen the pedestrian walk interval by 5 to 8 s.	Vision-impaired pedestrians require more time to prepare for crossing and tend to start crossing later.
Use an APS implementation consistent with features in figure below and with recommendations from Barlow, Bentzen, and Tabor (*1*).	Poorly implemented APSs can lengthen the time that vision-impaired pedestrians require for crossings.

Note: Chapter 6 of Barlow et al. (*1*) has additional recommendations regarding walk indications (including location, tones, speech messages, vibration surfaces, volume, and audible beaconing) and other APS features (including pushbutton locator tone, tactile arrow, pushbutton information message, automatic volume adjustment, alert tone, actuation indicator, tactile map, Braille and raised-print information, extended button press, passive pedestrian detection, and clearance interval tones).



The figure below shows the ideal placement of pushbutton integrated APS and recommended positioning of curb ramps (from Barlow et al. (*1*)).



Discussion

Curb ramps: Aligning themselves with the crosswalk and staying within it are some of the biggest challenges that vision-impaired pedestrians face at intersections. One study found that only 66% to 75% of pedestrians started within the crosswalk, started from an aligned position, traveled within the crosswalk, and ended within the crosswalk (*2*). Two factors that contribute to these problems are large-radius corners that eliminate important cues for alignment, and curb ramps that do not line up with the crosswalk, which make finding the crosswalk more difficult for vision-impaired pedestrians (*3*). Factors that help vision-impaired pedestrians detect the crosswalk location include a ramp slope that has a steep angle, an abrupt rate of change in the slope between the approach to each curb and the ramp itself, and curb ramps aligned with the crosswalk (*4*).

O'Leary, Lockwood, and Taylor (*5*) found that domed surfaces were far more detectable than rough aggregate surfaces and that a majority of the totally vision-impaired participants failed to detect either of two exposed rough aggregate surfaces.

Signal timing: Vision-impaired pedestrians can cross at the same speed as other pedestrians (4 ft/s), but they require additional time before crossing to determine that it is safe to cross (by listening to the near-side parallel vehicle surge). This additional time can result in pedestrians leaving the curb during the clearance interval after the initial "walk" interval has passed. Bentzen, Barlow, and Bond (*2*) found that mean starting delay ranged from 5 to 8 s and resulted in 26.2% of all crossings being completed *after* the onset of perpendicular traffic.

APS: As indicated in the guideline, recommended characteristics for APSs (e.g., location, tones, speech messages) and associated pushbuttons (e.g., locator tone, tactile arrow, information message) are covered in detail in Barlow et al. (*1*). These recommendations address important difficulties that vision-impaired pedestrians encounter with APSs and pushbuttons. In particular, common problems with APSs include (1) identifying which crosswalk had the signal, (2) hearing a signal that is too quiet, (3) remembering which sound is for which direction, and (4) finding the APS (*6*). Additionally, common problems with pushbuttons include (1) not being able to determine if a pushbutton is present, (2) locating the pushbutton, (3) identifying which crosswalk is actuated by the pushbutton, and (4) having insufficient time to prepare for crossing because pushbuttons are located too far from the crosswalk (*6*).

Design Issues

The MUTCD (*7*) states that APS implementation should be based on engineering studies that consider the following factors: (1) potential demand for accessible pedestrian signals; (2) a request for accessible pedestrian signals; (3) traffic volumes during times when pedestrians might be present, including periods of low traffic volumes or high turn-on-red volumes; (4) the complexity of traffic signal phasing; and (5) the complexity of intersection geometry.

Additional guidance about locations that may require APSs are presented in Barlow et al. (*1*) and include the following:

- Intersections with vehicular and/or pedestrian actuation
- Very wide crossings
- Non-rectangular or skewed crossings
- T-shaped intersections
- High volumes of turning vehicles
- Major streets at intersections with low-traffic minor streets (an APS may be needed for crossing the major street)
- Split phase signal timing
- Exclusive pedestrian phasing, especially where right-turn-on-red is permitted
- A leading pedestrian interval

Cross References

Countermeasures for Improving Accessibility for Vision-Impaired Pedestrians at Roundabouts, 10-10

Key References

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CHAPTER 12

Interchanges

TASK ANALYSIS OF DRIVER MERGING BEHAVIOR AT FREEWAY ENTRANCE RAMPS

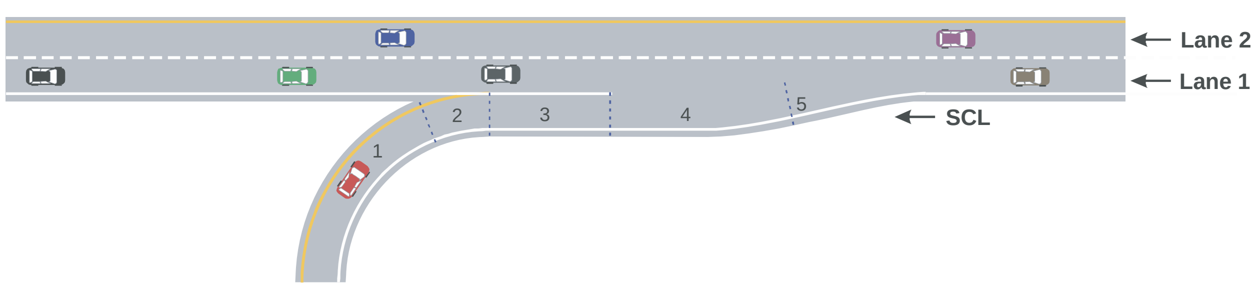
Introduction

Merging from an entrance ramp onto the freeway mainline can be a challenging task for drivers. For example, 36% of all ramp accidents on urban interstates in Northern Virginia occurred when drivers were entering the freeway (*1*). In addition, simulator data showed that, when merging, drivers move their hands to positions in which they can exert more vehicle control (*2*). Although the driver task can be broken up into a series of subtasks, the process is more dynamic than mechanistic: both mainline and merging drivers can detect the gaps available and decide to change their speed accordingly.

Design Guidelines

Task	Distance/Time Derivation	Driver and Roadway Factors
1. *Initial steering component*: Drivers steer to transition from the entrance ramp to the Speed-Change Lane (SCL).	• Constant time of approximately 1 s, derived from research.	NA
2. *Acceleration*: Drivers accelerate to obtain an unobstructed view of mainline freeway traffic.	• Time determined by the travel distance required to see approaching vehicles on the mainline. • The observed 85th percentile maximum comfortable acceleration is 2.0 m/s^2 (*3*).	• Affected by the controlling ramp curvature (*4*).
3. *Gap search*: After seeing the ramp nose, drivers begin to search for a gap in the mainline traffic to use for their merge.	• 0.25 to 0.5 s is required to detect the angular velocity of the lag vehicle on the freeway mainline.	• No stable base for judging speed/position of freeway vehicles (*4*). • Drivers who force in accept smaller gaps and accelerate (*5*). • With heavy congestion, zip merging at ramp end happens instead of gap search (*6*).
4. *Merge steering*: Drivers steer to transition from the SCL to the freeway mainline.	• 85% of observed vehicles merge comfortably in 375 m (*7*). • SCL lengths over 425 m do not improve merging behavior (*7*).	On tapered ramps vs. parallel ramps: • A greater ramp length is used to merge (*8*). • Drivers merge more aggressively (*9*).
5. *Abort*: Drivers who do not find a gap to merge into decelerate to a stop before running out of SCL.	• Time determined by the angular velocity of the approaching ramp end.	NA

SUBTASK LOCATIONS



Source: adapted from Ahammed et al. (*3*)

Discussion

Initial steering component: The initial steering component occurs when drivers transition from the entrance ramp onto the SCL. This steering time is approximately 1 s in length, derived from empirical research on steering (*4*).

Acceleration component: During the acceleration component, drivers accelerate to obtain a view of the mainline traffic on the freeway. This acceleration is controlled by the ramp curvature (*4*). Additionally, drivers cannot begin the next component, gap search, until they have an unobstructed view of the mainline traffic. Hunter and Machemehl (*7*) found that ramps with adequate sight distance and SCL lengths led to small acceleration levels, while ramps without adequate sight distance and SCL lengths caused larger positive and negative acceleration levels.

Gap search component: In general, drivers do not begin searching for a gap in the mainline traffic until they can see the nose of the entrance ramp (*10*). On cloverleaf ramps, drivers focus on navigating the curves until they are on a transition spiral to the straight portion of the lane (*10*).

Merge steering component: Two types of merges have been described in the literature. The first, a short merge, occurs when the driver merges before or near the end of the entrance ramp nose. This type of merge is likely to occur on ramps with poor geometry where drivers merge aggressively to avoid being trapped at the end of the lane (*11*). The second type, the long merge, occurs when the driver uses almost the entire length of the acceleration lane. This type of merge occurs when the geometry is good and traffic volumes are high (*11*). Sarvi et al. (*6*) suggest that when there is heavy congestion, gap search does not actually occur; instead, zip merging happens at the end of the ramp (i.e., where ramp and freeway vehicles merge one by one in an alternating pattern). There is some disagreement as to which geometric component has the greatest effect on gap acceptance: right lane volumes (*11*), ramp design (*6*), or gap distribution (*4*). Overall, Hunter and Machemehl (*7*) found that 85% of entering vehicles merged comfortably in 375 m as measured from the point where the ramp and mainline pavement edges are 1.25 m apart to the end of the taper. Limited-length SCLs over 425 m are not necessary to improve merging behavior.

Abort component: The abort maneuver only occurs if drivers do not find a suitable gap within the length of the SCL. Their focus changes from gap search to an avoidance maneuver and they decelerate to stop before the end of the SCL (*4*).

Design Issues

Merging speeds of elderly drivers are lower than those of younger drivers when there are no cars in the mainline right lane. These speeds decreased further when there were cars on the through lane. Merge point distributions were similar for young and old drivers (*12*).

Cross References

Key Components of Sight Distance, 5-2

Key References

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REDUCING WRONG-WAY ENTRIES ONTO FREEWAY EXIT RAMPS

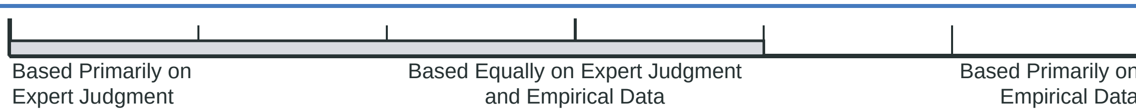
Introduction

Reducing wrong-way entries onto freeway exit ramps refers to treatments that can be used to reduce the frequency of drivers entering freeways by using the exit ramps. An average of 350 fatalities occur each year in the United States as a result of wrong-way crashes on freeways (*1*). Furthermore, exit ramps were found to be the most frequent origin of wrong-way incidents. In the sample of wrong-way drivers, elderly drivers are overrepresented by experiencing twice the wrong-way crashes than would be expected. Crashes often occur in the early morning hours, although this may be linked with the high frequency of impaired drivers.

Design Guidelines

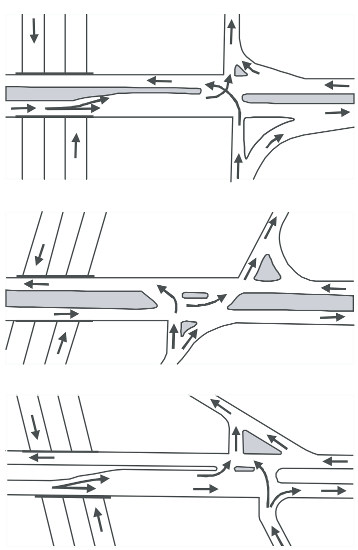
This guideline can be used to identify roadway treatments or geometric countermeasures that address specific issues contributing to wrong-way driving, thereby reducing the occurrence of drivers entering freeways via exit ramps.

Issues Contributing to Wrong-Way Driving (*2*)	Roadway Treatments or Geometric Countermeasures
Light land use Low traffic volumes	• Increase conspicuity, e.g., use wrong-way arrows or red reflectorized raised pavement markings (RRPMs) (*3*) • Monitor interchanges in areas of light land use and low traffic volumes
Poor visibility	• Increase/improve roadway lighting
Adequate directional signing (except at driveways)	• Lower "Do Not Enter" and "Wrong Way" signs (*4*)
Confusing or poorly visible access point configurations	• Avoid freeway left-side exit ramps (*4*) • Provide more cues using the ramp geometry (e.g., more severe angles on the right side as the vehicle passes the exit ramp on the roadway; *5*) • Median installations (*6*)

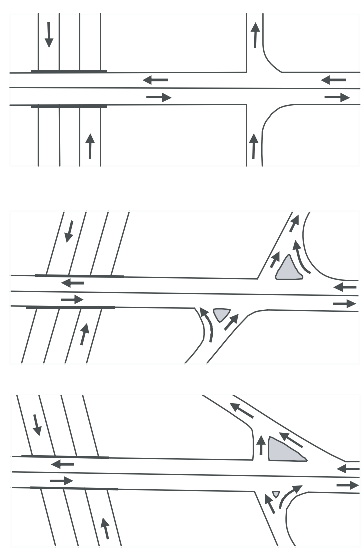


GEOMETRIES TO DISCOURAGE WRONG-WAY ENTRY

Divided Crossroads



Two-Lane Crossroads



Source: recreated from AASHTO (*5*)

Discussion

All of the characteristics listed in the guideline on the previous page correspond to missing cues that can help drivers determine that they have started down the roadway, particularly an exit ramp, in the wrong direction.

Light land use and low traffic volumes: Wrong-way driving crashes tend to occur in areas with light land use and low levels of traffic. Both of these situations likely indicate occasions when few cars would be traveling in the opposing direction to signal to drivers that they are going to be traveling the wrong way. In these cases, drivers need another indication that they have started traveling in the wrong direction. In a laboratory study of straight multilane roads, Miles, Carlson, Ullman, and Trout (*3*) found that the addition of directional arrows or red RRPMs led to more correct identifications of the proper travel direction on a roadway, though the effects were moderate.

Poor visibility: Wrong-way movements tend to occur when visibility is poor (*2*). In a study of wrong-way crashes, 74% were found to occur during the dark hours of the day. An obvious potential solution is to increase the level of artificial lighting at the access points. An increase in lighting levels would make some of the cues that are available to drivers more apparent at nighttime.

Adequate directional signing: Scifres and Loutzenheiser (*2*) found that in most cases, the signing at most of the origins was adequate (with the exception of driveways). However, signing improvements have been suggested by Cooner, Cothron, and Ranft (*4*). Notably, they refer to a lower mounting of “Do Not Enter” and “Wrong Way” signs, shown to be effective in the state of California. The lower height avoids sight restrictions, is in the range of low-beam headlights for night driving, and is potentially more visible to impaired drivers who drive with their eyes on the pavement. The bottom of the sign package is installed 2 ft above the edge of the pavement (though this is inconsistent with the MUTCD).

Confusing or poorly visible access point configurations: Wrong-way movements were increased when the design of the access point was difficult to see or understand (*2*). The simplicity of the access points can be improved in multiple ways. The first is to avoid the construction of left-side exit ramps and install reflectorized wrong-way pavement arrows on existing left-side ramps (*4*). During a crash analysis, left-side exits experienced multiple crashes due to wrong-way entries. Drivers are familiar with turning right to enter a freeway and may end up traveling the wrong way up a left exit ramp by using this maneuver. Additionally, AASHTO (*5*) recommends sharp or angular intersections between the crossroad and the ramp, making the incorrect maneuver less natural to execute. Median islands can also make incorrect turning movements more difficult. The diagrams on page 12-4 provide sample road geometrics that discourage wrong-way entry.

Design Issues

Drivers who are under the influence of alcohol and/or other drugs compose a considerable portion of wrong-way drivers. Although these drivers cannot specifically be designed for, countermeasures that reduce the affordance of driving the wrong way (such as geometric alterations) may be more effective than those which require the perceptual abilities of the drivers to function at a certain level (such as signage or pavement markings). These trade-offs can be considered in areas near bars or other locations where drunk drivers may be more prevalent.

Short sight distance has been found to be a contributor to wrong-way crashes (*7*). Improving sight distance may decrease the number of drivers driving the wrong way by increasing the odds that they will see an approaching right-way driver’s headlamps. However, improving sight distance is more of a crash avoidance measure for right-way drivers who will see wrong-way drivers approaching from a greater distance.

Cross References

Lighting Guidelines, 21-1

Key References

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DRIVER EXPECTATIONS AT FREEWAY LANE DROPS AND LANE REDUCTIONS

Introduction

Matching *driver expectations at freeway lane drops* is important because lane drops represent a situation that may violate driver expectations and cause confusion when the driver expects the lane to continue on the freeway mainline. This confusion can result in high speed variability, erratic maneuvers, and driver frustration (*1*). Additionally, a left lane drop situation violates multiple driver expectations and can cause more problems. All of these results have negative safety implications; thus, the more accurately that lane drops conform to driver expectations, the safer the situation will be. This guideline refers specifically to lane drops on freeway sections that do not include exit ramps.

Design Guidelines

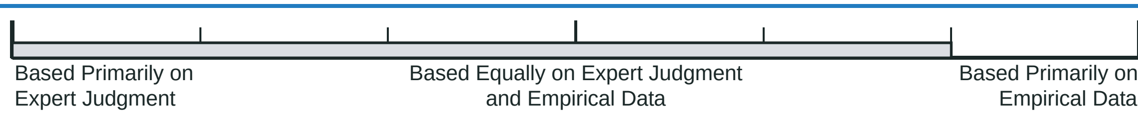
Consideration should be given to the following principles related to lane drops and lane reductions to promote driver behavior that is consistent with the safe use of such facilities (based on Goodwin (*2*)).

Principle	Guideline
Visual Principles	
Provide continuous visibility	The minimum distance that should be visible to a driver is that required to: a. Perceive that the lane is ending, b. Evaluate maneuver options, and c. Maneuver to an adjacent lane.
Minimize attention-dividing conditions	Place the lane drop away from other distractions such as ramps or complicated signage.
Provide adequate transition cues	Provide a taper of sufficient length so that drivers who enter it with no knowledge of the lane drop will have sufficient time to maneuver.
Coordinate the visual and operational drop	Create a lane reduction such that the lane does not appear to continue beyond the operational reduction, even if the pavement does continue.
Geometric Principles	
Provide an adequate escape area	Provide an adequately sized escape area at exit lane drops for drivers who have insufficient time before the exit gore to make a normal lane change.
Signing Principles	
Notify the driver that the lane is not continuous	Warn drivers who enter the freeway by using an add-drop lane that the lane is not a permanent addition.
Use adequate traffic control devices	Use adequate and consistent traffic control devices to inform drivers: a. What is going to happen b. Where it is going to happen, and c. What they need to do.

SPECIFIC GUIDANCE FOR LANE DROPS AT EXITS WITH OPTION LANES

For lane drops with option lanes, clearly communicate (*3*):

1. The dropped lane can only reach the exit
2. The option lane leads to either the exit destination or the mainline
3. Any other lane only reaches the mainline
4. The identifying information for each destination (e.g., street name, destination name)



Discussion

It should be noted that the lane drop guidance provided by Goodwin (*2*) is not specific to exit lane drops as they are commonly referred to today. This guidance was also formulated based on the study of lane reductions on freeways.

Visual principles: Lane drops should be located where drivers can see them continuously for a long enough period of time to perceive that the lane is about to end, decide on a maneuver, and execute that maneuver. Thus, lane drops should not be located just over the crest of a vertical curve or around a horizontal curve (*2*). Lane drops should be located away from other conditions which require the driver's attention, as these locations increase the probability of drivers missing lane drop cues while looking at other roadway features. A major visual cue for navigating lane drops is the lane drop taper. An inappropriately short taper may cause drastic lane changes, while an overly long taper does not provide cues that the lane is ending. From the driver's viewpoint, operational and physical lane reductions should be coordinated. So, if the pavement continues beyond the operational lane drop, it should be apparent that the lane does not continue onto that pavement.

Geometric principles: Cornette (*4*) found that lane drops, lane splits, and lane reductions at sites with poor geometrics (i.e., high rates of curvature, sight distance restrictions) had higher conflict rates than those at sites with better geometric features. Drivers who do not expect the lane drop should have a reasonable opportunity to recover and stay on their route. An adequate escape area should be provided at/after an exit lane drop to provide drivers who do not want to exit a chance to recover and remain on the mainline (*2*).

Signing principles: A subset of the drivers who encounter a lane drop may have just entered the freeway. If drivers are able to enter using an add-drop lane, they should be warned that their lane is not continuous for through travel (*2*). For all drivers, adequate and consistent information should be provided by the traffic control devices. It is important for drivers to know if they are required to take an action, or if other drivers are required to act. Additionally, excess information not related to the lane drop segment should be minimized (*2*).

Lane drop exits with option lanes provide particularly difficult circumstances for drivers. It is often unclear to drivers that the option lane serves both the mainline and the exit destinations. The underutilization of the option lane can lead to a loss of service volume for the roadway as well as a number of unnecessary merge maneuvers.

Design Issues

On United States border roadways that are used by a large percentage of Spanish-speaking drivers, additional signage with Spanish legends may be appropriate. To convey the message "Right Lane Ends," the sign that had the highest overall comprehension level among Spanish-speaking drivers was "Carril Derecho Termina" (*5*). This sign also had the highest comprehension levels among English-speaking drivers among the three Spanish-legend signs that were tested.

Dynamic late-merge systems have been developed for use in work zone lane closure situations. These systems utilize a series of changeable message signs and static work zone signs to provide merge information to the driver based upon the current traffic volume through the work zone. The basic principle supports early merging when the traffic flow is light and late merging (closer to the gore point) when the traffic volume is heavier.

Cross References

Passing Lanes, 16-2
Effectiveness of Symbolic Markings, 20-4

Key References

1. Chrysler, S.T., Williams, A.A., Funkhouser, D.S., Holick, A.J., & Brewer, M.A. (2007). *Driver Comprehension of Diagrammatic Freeway Guide Signs*. College Station: Texas Transportation Institute.
2. Goodwin, D.N. (1975). Operational effects of geometric design at freeway lane drops (Abridgment). *Transportation Research Record, 541*, 26-30.
3. Upchurch, J., Fisher, D.L., & Waraich, B. (2005). Guide signing for two-lane exits with an option lane. *Transportation Research Record, 1918*, 35-45.
4. Cornette, D.L. (1972). *Operational Characteristics of Lane Drops.* (KYHPR-70-63, HPR-1(18), Part II). Lexington: Kentucky Bureau of Highways.
5. Hawkins, H.G., Jr., Picha, D.L., Kreis, D.C., & Knodler, M.A. (1999). *Evaluation of Alternative Traffic Signs for Use in Texas Border Areas.* (FHWA/TX-99/1274-3). College Station: Texas Transportation Institute.

DRIVER INFORMATION NEEDS AT COMPLEX INTERCHANGES

Introduction

Accommodating driver expectations at interchanges is paramount to navigational success. Expectations refer to "a driver's readiness to respond to situations, events, and information in predictable and successful ways" (*1*). Complex interchanges should be designed to give the drivers what they expect to see (*2*). Information that reinforces expectancies helps drivers respond faster, whereas information that violates expectancies leads to longer task times and/or errors (*3*). Thus, more predictable design and operation leads to fewer errors (*4*).

Design Guidelines

Geometric Elements

Route continuity:
- Provide a route on which changing lanes is not necessary to continue on the through route (*5*).
- If possible, provide the greatest number of lanes for the through movement (*6*).

Lane balance:
- "The number of lanes leaving a diverge point is equal to the number of lanes approaching it, plus one" (*7*; see figure).
- Minimize the required number of lane shifts by using option and auxiliary lanes (*6*).

Ramp spacing:
- Provide adequate ramp spacing to allow for clear and simple guide signing, and to prevent congestion from heavy traffic entering and exiting (*6*).

Error handling:
- Provide a forgiving roadside at critical features (*2*).
- Avoid creating compound geometric features (*2*).

Signing

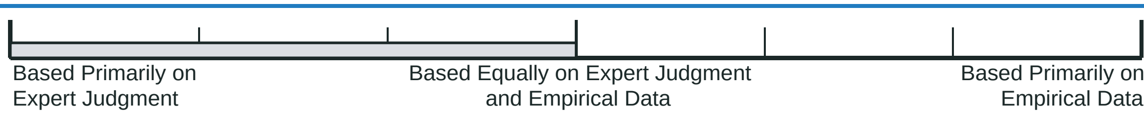
Error handling:
- Eliminate information-related error sources: avoid deficient, ambiguous, confusing, missing, misplaced, blocked, obscured, small, illegible, or inconspicuous displays (*3*).

Sign placement:
- Spread out competing information sources by moving less important information upstream or downstream (*3*).
- Structure driver expectations through advanced warning (*4*).
- Repeat important information or do not provide interchange information so far upstream that it is forgotten by the time that the interchange is reached (*3*).

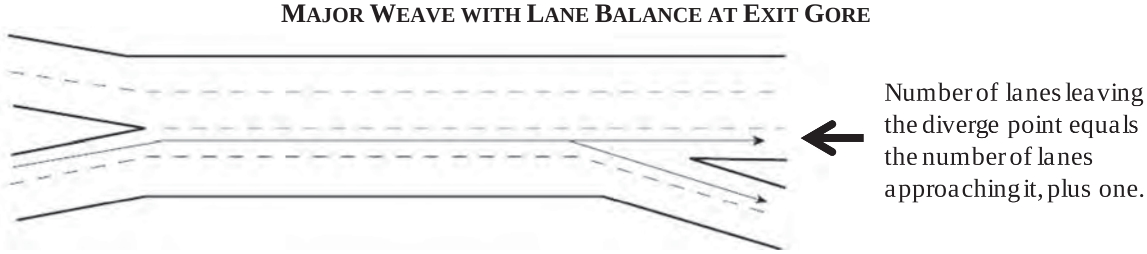
Sign content:
- Provide appropriate signing to guide drivers (*2*).
- Satisfy all driver information needs (*3*).

Sight Distance

- Avoid sightline restrictions (*1*).
- Provide visibility that is proportional to feature criticality (*2*).



MAJOR WEAVE WITH LANE BALANCE AT EXIT GORE



Source: Transportation Research Board (*7*)

Discussion

Overall, there is little information available in the research literature that provides specific guidance related to supporting driver expectations at interchanges. The information provided in the guideline on the previous page is generally related to principles of geometry, signage, and sight distance to support elements of driver expectations at interchanges.

Geometric elements: Doctor, Merritt, and Moler (*6*) discuss driver expectations in reference to multiple elements of interchange design. Ramp spacing that is too close can lead to congestion and cluttered signage. The combination of system and service interchanges can lead to information overload, inconsistent sign design, and contradictory movements. Route continuity is provided by designing a roadway on which "changing lanes is not necessary to continue on the through route" (*5*). This principle "reduces lane changes, simplifies signing, delineates the through route, and reduces the driver's search for directional signing" (*5*). Additionally, drivers sometimes assume that at a split, the leg with the greater number of lanes carries the main route. To use lane balance, designers arrange the lanes on the freeway to require drivers to take the minimum number of lane shifts. This is done by using option and auxiliary lanes.

Signing: Advance guide signing that prepares drivers to make decisions and maneuvers is possibly the most important strategy for helping drivers navigate complex interchanges (*6*). Signing can spread out the amount of time that drivers can use to perform lane changes in advance of the decision points. Additionally, signs at the decision point confirm decisions that drivers made on the approach (*6*). Lunenfeld (*3*) stresses that the amount of information should not overwhelm the driver. When information sources compete, the less important sources should be moved upstream or downstream. However, information should not be provided so far upstream that it is forgotten by the time that the interchange is reached. If information is too far upstream, it may need to be repeated closer to the interchange.

Sight distance: Adequate sight distance is required due to the reliance on visual information and for complex decision making (*3*). Sightline obstructions that cover up important or critical information cues should be avoided.

Design Issues

In particular, driver expectations can be easily violated at transition sections where the roadway conditions change. Drivers anticipate the upcoming roadway characteristics based on features that are common to the road they are on (*4*). Roadway designers should look for possible expectancy violations where changes in roadway characteristics (e.g., geometrics, design, or operation) or changes in operating practices occur (e.g., speed zones, no passing zones, or signal timings; *1*). Features that are "first of a kind" on a particular roadway or those that drivers may find unusual or special are also important to examine (*1*). Additionally, adequate transitions should be provided (*2*).

Cross References

Sight Distance Guidelines, 5-1
Driver Expectations at Freeway Lane Drops and Reductions, 12-6
Signing Guidelines, 18-1

Key References

1. Lunenfeld, H., & Alexander, G.J. (1984). Human factors in highway design and operations. *Journal of Transportation Engineering, 110*(2), 149-158.
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3. Lunenfeld, H. (1993). Human factors associated with interchange design features. *Transportation Research Record, 1385*, 84-89.
4. Cline, E.L. (1999). Adherence to design standards and guidelines: The human factor. *69th ITE Annual Meeting.*
5. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.
6. Doctor, M., Merritt, G., & Moler, S. (2009). Designing complex interchanges. *Public Roads, 73*(3), 3-11.
7. Transportation Research Board (2000). *Highway Capacity Manual 2000*. Washington, DC.

ARROW-PER-LANE SIGN DESIGN TO SUPPORT DRIVER NAVIGATION

Introduction

Arrow-per-lane (APL) signs are composed of primarily two parts: arrows that point to individual lanes, and the destination information listed above the arrows. They generally either are large signs or occur in groups, because every individual lane requires its own arrow. These signs provide clear direction for the destinations reached by each lane and have been shown to increase the number of correct lane choices by older drivers as compared to standard diagrammatic signs (*1*). The signs shown in the guideline vary slightly from those recommended by the MUTCD (*2*), because they are modeled after real sign examples. Therefore, this guideline is focused on troubleshooting driver issues rather than informing new sign design.

Design Guidelines

To effectively support driver navigation, the destination information and sign design must allow drivers to pair the destination information with an arrow, and consequently, an arrow with a travel lane.

PAIRING DESTINATION INFORMATION WITH ONE OR MORE ARROWS

Poorly Distinguished Information		Easily Associated Information	
Unsymmetrical centered text above split text:		*Text centered above one or more arrows:*	
	• 30 West shield can be interpreted to apply only to left lane.		• Centered text is easily matched to one or more arrows.
Hyphenated destinations:		*Stacked and centered text:*	
	• Hyphenated destinations may cause driver confusion.		• Stacked destinations are interpreted to go with both arrows.
"Exit Only" by one of multiple arrows:		*Exit placard centered above a panel:*	
	• "Exit Only" notation may be associated with the destination rather than the arrow.		• A centered exit placard is interpreted to apply to the entire sign.

PAIRING ARROWS WITH TRAVEL LANES

Causes of Driver Confusion	What to Do to Fix It
Arrows do not appear to be centered over the lanes.	On tangents, make sure that the arrows are centered over the lanes from the time when the sign is first legible until the driver passes the sign (for legibility distance calculations, see Tutorial 5). Avoid APL signs on sharp horizontal curves.
All of the destinations above an arrow are not reachable by using that lane.	Avoid positioning a destination above an arrow if it can't be reached by the indicated lane.
All of the destinations above an arrow are not able to be reached by following the same direction at a split or option lane.	Match the layout of the destination information to the roadway geometry.

Discussion

The drivers' reading goal is to associate destination information with an arrow which points to a particular lane. To accomplish this goal, the pertinent destination information must be able to be separated from adjacent information and clearly pertain to one or more arrows. The primary sign feature that accomplishes this is the centering of information above the applicable arrows. In essence, destinations are interpreted as being centered above the arrow(s) to which they apply. Design elements that cause inappropriate continuity or separation between elements make the navigation task more difficult. The figure on page 12-10 shows both good and bad examples of pairing destination information with arrows.

Poorly distinguished information: Sign layout can make destination information more difficult to associate with the relevant arrows. One way in which this may occur is when destination information that is meant to be shared by multiple arrows (i.e., more than one lane leads to the same destination or destinations) is interpreted by drivers to mean that each lane leads to a different destination. For example, with the 30 West notation in the guideline, the entire text segment is centered on the sign. Some drivers, however, may interpret the route shield as being more toward the left side of the sign and associate the route with only the left-hand arrow rather than both arrows because the route shield is much larger than the "west" notation. Another problem may occur when text and associated arrows that are meant to indicate different destinations are interpreted by drivers to indicate multiple lanes that lead to the same destination. Destination groupings that are separated by a hyphen may lead to this kind of confusion. The destinations can be interpreted as two areas on the same roadway, or two separate areas. The hyphen prevents association with a single arrow by creating continuity between destination names. Thus, it should be avoided.

In Richard and Lichty (*3*), a situation arose where the "Exit Only" indication was positioned above a single lane on a multiple-APL sign. Drivers interpreted this "Exit Only" text in a different way than the destination information when used above a single arrow; rather than applying this information to the arrow, and thus the travel lane, drivers assigned it to the destination(s). Therefore, this positioning may cause some drivers to believe that they need to be in the exit-only lane to reach the destination, causing unnecessary lane changes.

Easily associated information: In Richard and Lichty (*3*), destination information shown directly above an arrow was associated by all drivers with the lane below the arrow. Drivers thought that an arrow with multiple destinations meant that all of the listed destinations could be reached using that lane. Similarly, information that was centered above multiple arrows was generally seen as applying to all of the arrows that it was centered above. This applied to destination information above multiple arrows or smaller placards above larger guide signs that referred to the entire guide sign.

The signs included in the guideline section on the previous page are modeled after real sign examples. It should be noted that they vary slightly from those recommended in the MUTCD (*2*). For example, those included show downward pointing arrows, whereas the MUTCD recommends upward pointing arrows except in cases where the lane use is restricted to the listed destinations. The direction that the arrows point should not have an impact on the visual grouping performed by drivers. The MUTCD has additional guidance recommending using only one destination per movement; however, multiple destinations listed per movement are common on existing signs. This guideline does not seek to contradict the MUTCD with design guidance, but rather to discuss general interpretation patterns and provide guidance for troubleshooting problematic signs and prioritizing their replacement.

Design Issues

Separations between sign panels can also be used to distinguish between lanes or lane groupings. Destinations on different panels are typically not associated with one another (*3*). Splits between sign panels also show where "Exit" placards apply and do not apply. The MUTCD (*2*) describes the usage of a vertical white line to separate diverging route movements. This is likely comparable to the distinction between separate sign panels.

Cross References

General Principles for Sign Legends, 18-2
Driver Comprehension of Signs, 18-8

Key References

1. Golembiewski, G., & Katz, B.J. (2008). *Diagrammatic Freeway Guide Sign Design.* Traffic Control Devices Pooled Fund Study. Retrieved July 2011 from http://www.pooledfund.org/projectdetails.asp?id=281&status=4.
2. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
3. Richard, C. and Lichty, M.G. (2011). Driver expectations when navigating complex interchanges. Task 4: Gather feedback from drivers. Draft report (Federal Highway Administration Contract No. DTFH61-08-D-00032-T-10005). Seattle, WA: Battelle.

DRIVER BEHAVIORAL TRENDS BASED ON EXIT RAMP GEOMETRY

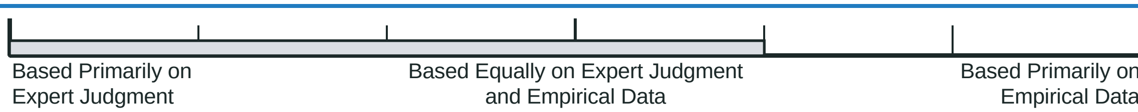
Introduction

Exit ramps provide the means of accessing adjacent surface streets from a freeway. Well-designed exit ramps provide sufficient area for vehicles to depart from the main freeway lanes and sufficient distance for vehicles to decelerate comfortably from freeway speeds to a speed appropriate for the controlling feature of the ramp, which may be the first curve encountered along the ramp or it could be the crossroad terminal. Driver behavior at freeway exit ramps is based upon a variety of factors, including the operating conditions along the freeway and the geometry of the ramp.

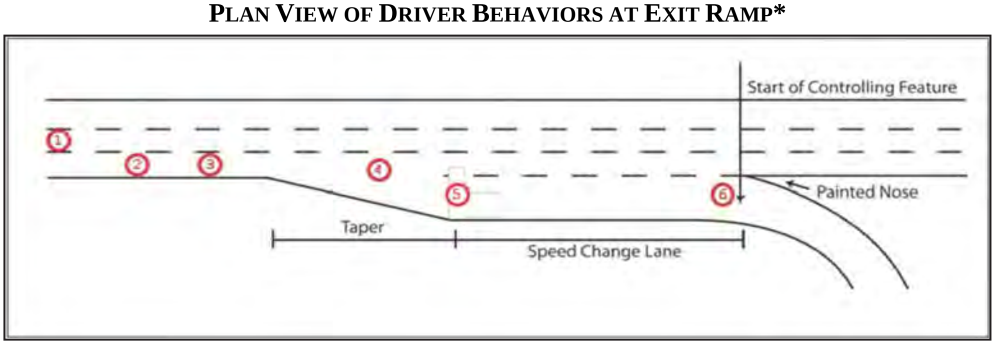
Design Guidelines

To design exit ramps, it is important first to define the intended behaviors of an exiting driver (*1*). Ramps should be designed accordingly to support these safe driving behaviors. The figure highlights where key driver behaviors/decisions take place in the vicinity of an exit ramp. The numbers in the figure correspond to the driver behaviors listed in the first column of the table.

Driver Behaviors for Safe Exit	Design Features to Support Safe Driving Behaviors
1. The driver should maintain a relatively constant speed in the freeway lanes. 2. The driver should position his/her vehicle in the right lane of the freeway prior to the beginning of the deceleration lane. 3. The driver should signal to indicate his/her intended maneuver to other drivers in the traffic stream. 4. The driver should initiate the diverge maneuver shortly after the deceleration lane begins. 5. Deceleration should begin gradually, immediately after entering the deceleration lane. 6. The driver should reach ramp speed before the end of the deceleration lane.	1. Proper sequence and location of guide signs to allow drivers time to make proper route choice decisions. 2. Sufficient sight distance to allow drivers to perform appropriate maneuvers. 3. Pavement markings and roadside delineation to delineate the proper trajectory along the ramp. 4. Delineation to distinguish the features of the gore area. 5. For taper-type exits, sufficient divergence angle to provide a clear indication of the point of departure from the through lanes. A typical divergence angle is usually between 2 and 5 degrees. 6. For parallel-type exits, a taper area should be provided to indicate the general path to be followed by the exiting driver. Typical taper lengths are between 15:1 to 25:1 [longitudinal:transverse]. 7. Deceleration lane lengths sufficient for drivers to reduce their speed from the operating speed along the freeway to the average running speed of the controlling feature at the end of the speed-change lane. Minimum deceleration lane lengths are provided in Table 10-5 of the Green Book (*2*).



PLAN VIEW OF DRIVER BEHAVIORS AT EXIT RAMP*



*Numbers correspond to "Driver Behaviors" in the guideline above.

Design Guidance

On an exit ramp, deceleration is accomplished first as the driver removes his/her foot from the throttle and the vehicle coasts in gear for a period of time (typically) without the use of brakes, and then the driver applies the brakes and decelerates comfortably. A recent study (*3*) confirmed that drivers coast in gear an average of 3 s prior to applying the brakes to decelerate along a deceleration lane. Coasting time was defined to be the sum of the elapsed time between occurrence of peak speed and deactivation of throttle and the elapsed time between deactivation of throttle and activation of brake. Furthermore, drivers typically coast in gear approximately 2 s in the freeway lanes and approximately 1 s in the deceleration lane prior to applying the brakes.

Through further investigations of diverge locations and speeds and deceleration, Torbic et al. (*3*) concluded the minimum deceleration lane lengths provided in the 2004 Green Book (*4*) are conservative estimates, given the current vehicle fleet and driver population. Drivers decelerate at levels well within the capabilities of the vehicle fleet and driver preferences. This is, in part, due to some deceleration by drivers in the freeway prior to the diverge maneuver. Drivers typically diverge between 4 to 7 mi/h below average freeway speeds; however, it is prudent for designers to assume that all deceleration takes place in the speed-change lane when determining minimum deceleration lane length.

Although it seems intuitive that a relationship should exist between deceleration level and deceleration lane length, no relationship has been determined (*5*). It has been found that longer deceleration lanes lead to later deceleration at a higher level, perhaps because drivers relax thinking there is more time than there actually is to decelerate (*5*). Also, as deceleration lane length increases, the percentage of return maneuvers increases (*6*). On the other hand, shorter deceleration lanes lead to an increase in early exits (*6*) and deceleration along the taper to the lane. Torbic et al. (*3*) found similar results, indicating that providing deceleration lanes longer than the minimum values provided in the 2004 Green Book (*4*) may promote more casual deceleration by exiting drivers, particularly under uncongested or lightly congested conditions, but noted this is not necessarily a negative result. Simply, it changes the operational characteristics of the ramp.

Most drivers diverge from the freeway either within the taper or the first two-thirds of the speed-change lane (defined as the distance between the end of the taper to the painted nose). Few drivers diverge from the freeway in the final third of the speed-change lane or beyond the painted nose. Drivers that diverge earlier along the speed-change lane decelerate at a more casual level compared to drivers that diverge closer to the painted nose (*3*).

Design Issues

The current design criteria for exit ramps assume free-flow or uncongested conditions along the freeway and are based upon the vehicle capabilities of passenger cars and driver comfort levels. Several studies (*7, 8*) recommend longer deceleration lane lengths on the order of 15% to 50% longer than those required for passenger cars to better accommodate the reduced vehicle capabilities of heavy vehicles. However, when exiting the freeway, trucks decelerate at levels very comparable to those of passenger cars (*3*). In addition, truck drivers typically choose to diverge from the freeway at lower speeds than drivers in passenger cars and, during uncongested freeway conditions, the distribution of diverge locations for trucks is very similar to the distribution of diverge locations for passenger cars.

One of the goals in designing an exit ramp should be to minimize erratic behaviors near the ramp such as crossing gore paint, crossing gore area, stopping in gore, backing up, sudden slowing, lane changing (to exit), swerving, and stopping on shoulder. Erratic maneuvers occur most frequently after lunch, after rush hour, and during the first hour of darkness during mid-morning and mid-afternoon. These data suggest that most erratic maneuvers are made by motorists taking unfamiliar routes, as contrasted to shopping or commuting-to-work trips, which involve familiar and frequently used routes (*9*). Proper sequencing and location of overhead guide signs, good delineation of the exit ramp, and clearly distinguishing the taper, the beginning of the deceleration lane, and the gore area using pavement markings (e.g., raised pavement markers) and roadside delineation, in addition to geometrics, need to be considered to reduce driver confusion near exit ramps.

Cross References

Task Analysis of Driver Merging Behavior at Freeway Entrance Ramps, 12-2

Key References

1. Mace, D.J., Hostetter, R.S., & Sequin, L.E.. (1969). *Information Requirements for Exiting at Interchanges*. (Report 89211-f). State College, PA: HRB-Singer.
2. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.
3. Torbic, D.J., Hutton, J.M., Bokenkroger, C.D., Harwood, D.W., Gilmore, D.K., Knoshaug, M.M., et al. Design Guidance for Freeway Mainline Ramp Terminals. Final Report. NCHRP Project 15-31A. Washington, DC: Midwest Research Institute.
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CHAPTER 13

Construction and Work Zones

OVERVIEW OF WORK ZONE CRASHES

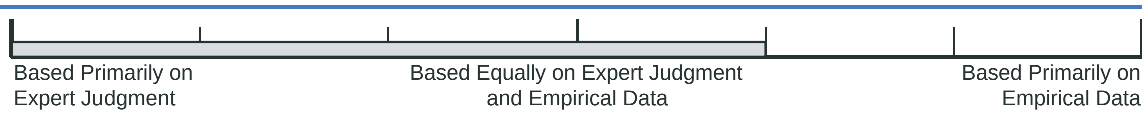
Introduction

This guideline provides a framework for characterizing *work zone crashes* and, by extension, provides guidelines for work zone design. It specifies the need for additional driver guidance in work zones based on the number, type and severity of crashes occurring in work zones. The typical work zone crash involves a male driver, age 25-34, who, while driving in clear weather during mid-afternoon on a US Highway or Interstate roadway, comes upon slow or stopped traffic due to construction and crashes into another vehicle. As discussed below, information provided by arrow panels, changeable message signs, and work zone speed limits are critical to safe and efficient work zone operations.

Design Guidelines

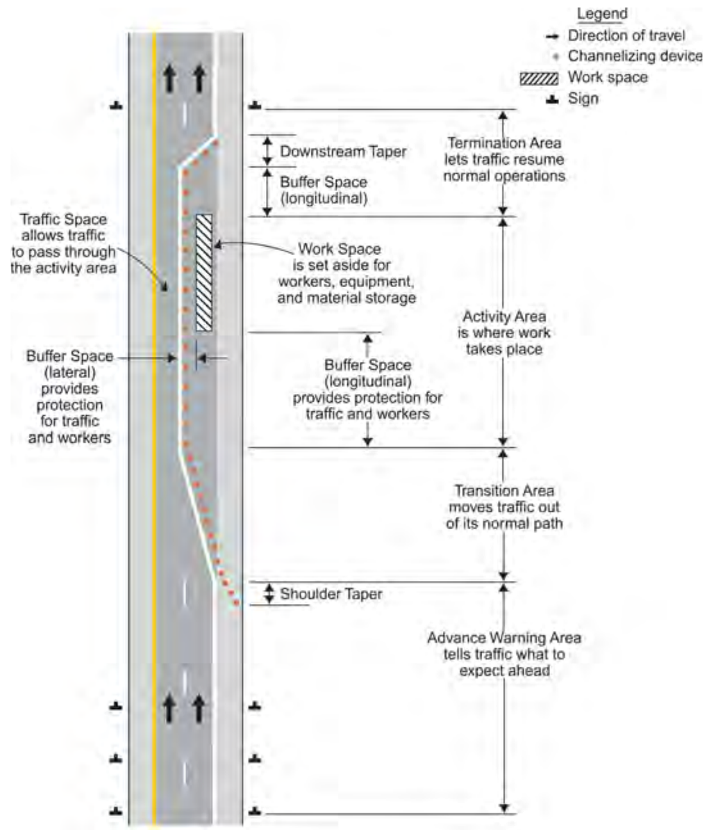
The table below summarizes characteristics of work zones and—for each—observed impacts on crash severity or frequency.

Work Zone Crash Characteristic	Observed Impact on Crash Frequency and Severity
General	Work zones increase both rear-end and fixed-object crashes.
Work Zone Area	The activity area is the predominate location of work zone crashes (see the figure on next page) – Signs should be used to give drivers advance warning of upcoming work zones.
Interstate Roadways	Many work zone crashes are on Interstate roadways – Selected positions of work zone signs should take into account roadway speeds and allow drivers to perceive and process the sign information.
Night Work	Before/during crash analysis did not reveal large increases in crashes during night work unless lanes were closed and significant traffic queues developed (*2*) – Caution modes on arrow panels can be used to warn drivers of temporary lane closures.
Car Following Patterns	Research on time gaps between cars in work zones in Illinois revealed a safety paradox: as vehicle speeds increase, time gaps between cars decrease from those observed with lower speed cars even though it takes longer to stop a higher speed car (*3*) – Selected work zone speed limits should maintain safe traffic flow and, usually, should be within 10 mi/h of normal speed limits.
Large Truck-involved Crashes in Work Zones	Truck-involved crashes are more likely to be multivehicle crashes than other work zone crashes. Truck-involved crashes are more likely to cause injuries when the crash occurs in the activity area as compared to crashes that occur in the advance warning area (*4*) – Longer stopping/slowing distances for heavy trucks imply greater advance warning requirements for work zones, especially on roadways used by heavy trucks.



Discussion

In discussions of work zone crashes, some research sources provide specific information about the driver behaviors related to crashes, in addition to the characteristics of overrepresented drivers (e.g., age, gender, etc). Other sources include the most frequent collision types, overrepresented types of vehicles (e.g., heavy trucks), and the involvement of other vehicles in work zone crashes. There is also information that is more specific to how work zone characteristics may contribute to driver-related factors, including lighting conditions, pavement markings, and the presence of warning signs or cones. Other aspects that are covered include the type of work zone activity in addition to crash characteristics by work zone area (advance warning area, transition area, longitudinal buffer area, activity area, and termination area). The remaining guidelines in this chapter focus on signing and speed limit information for work zones.



Source: FHWA (*1*)

COMPONENT PARTS OF A TEMPORARY TRAFFIC CONTROL ZONE

Design Issues

The rear-end crash is the predominate type of work zone crash. The design of work zones, particularity speed control methods and work zone speed limits, should reduce speed variance or cause drivers to drive at the same speed. This does not necessarily mean lowering the speed limit in the work zone, as a lower speed limit does not always result in a lower speed variance (*5*).

The study of fatal crashes in Texas work zones determined two design-related countermeasures: (1) design exits or refuge areas at regular intervals where shoulders are removed or no longer available for disabled vehicles and (2) use opposing lane dividers or arrow pavement markings at sites where the travel direction of a lane is changed temporarily, such as when lanes are closed and two-way traffic is handled in the remaining open lanes (*6*).

In general, the lack of consistency across states with respect to work zone signage is a problem that should be addressed in future research.

Cross References

Caution Mode Configuration for Arrow Panels, 13-6
Sign Legibility, 13-10
Determining Work Zone Speed Limits, 13-12

Key References

1. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC
2. Ullman, G.L., Finley, M.D., & Ullman, B.R. (2004). *Assessing the Safety Impacts of Active Night Work Zones in Texas* (FHWA/TX-05/0-4747-1). College Station: Texas A&M University.
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PROCEDURES TO ENSURE PROPER ARROW PANEL VISIBILITY

Introduction

Arrow panel visibility depends on a number of factors, including the capability of the lamps in the panel, the type of roadway, the physical location of the panel, the panel's relation to horizontal and vertical curves, ambient light, and weather. Procedures to ensure arrow panel visibility should include specifications for the arrow panel as well as field procedures to check in-service arrow panels.

Design Guidelines

ARROW PANEL SPECIFICATIONS
RECOMMENDED PHOTOMETRIC REQUIREMENTS

Time of Day	Speed (mi/h)	Minimum On-Axis		Minimum Off-Axis		Maximum On-Axis
		cd/lamp	cd/panel[a]	cd/lamp	cd/panel[a]	cd/panel[a]
Day	≥ 45	500	4000	100	800	NA
Night	≥ 45	150	1200	30	240	5500

[a] Intensity requirements for the entire panel when displaying a left or right flashing arrow (10 lamps illuminated)
Source: Wooldridge, Finley, Denholm, Mace, and Patrick (*1*).

Note: cd = Candela: the SI base unit of luminous intensity

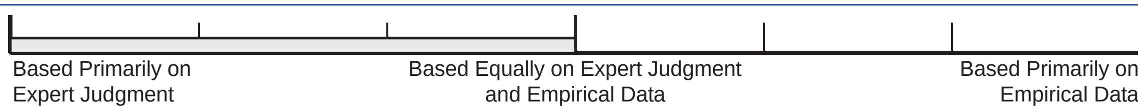
Angularity Requirements
- Minimum angularity permitted for a Type C (high-speed and high-volume roads) arrow panel should be +/– 4° in horizontal plane (8° beam width) and +/– 3° in the vertical plane (6° beam width).

Field Procedures
- Use of luminance to intensity measurements.
- Arrow should be oriented to be recognizable from 1500 ft even in curves (see figure below).

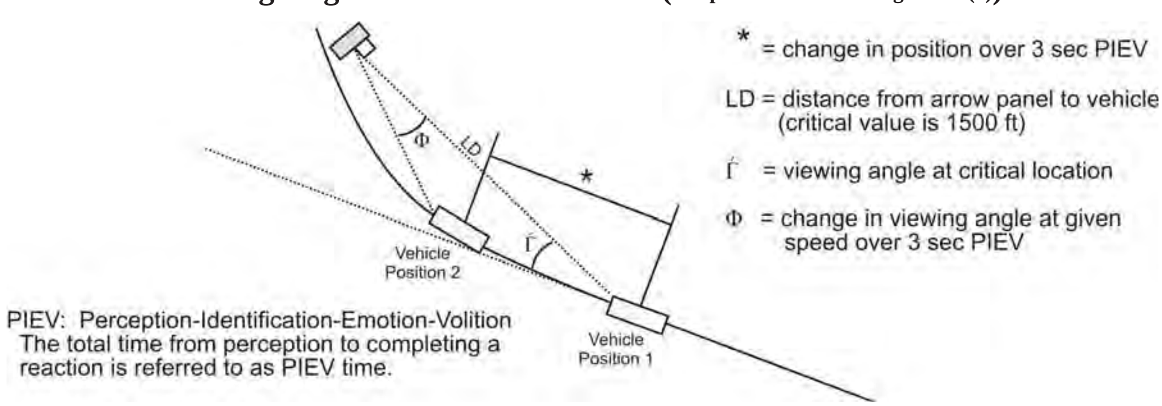
Effect of Arrow Panels
- In lane closures, arrow panels produced almost-ideal lane changing patterns.
- In traffic diversions, arrow panels produced some unnecessary lane changing.
- Arrow panels had little effect on traffic operations in moving shoulder closures on freeways.

Panel Luminous Intensity
- Field test resulted in recommendations for daytime of 4000 cd/panel as the minimum on-axis intensity and 800 cd/panel as the minimum off-axis intensity and a recommendation for nighttime of 5500 cd/panel as the maximum on-axis intensity.

Flash Rate
- 25 to 40 flashes/min.



Viewing Angle on Horizontal Curve (Adapted from Wooldridge et al. (*1*))



Discussion

Human factors studies conducted as part of this research are discussed in detail in Knapp and Pain (*2*).

In Graham, Migletz, and Glennon (*3*), the effect of arrow panels was judged in three situations: (1) when a lane is closed; (2) in diversions where the traffic route is modified without a lane reduction; and (3) in shoulder work zones. The following findings were reported:

- In lane closures, the presence of an arrow panel produced lane changing patterns that are closer to ideal. In other words, the arrow panel encouraged drivers to leave the closed lane sooner and, consequently, fewer lane changes occurred close to the lane closure taper.
- In traffic diversions, arrow panels produced some unnecessary lane changing; however, the number of these lane changes was small, particularly at night and for truck traffic. Overall, the use of arrow panels for diversions was not shown to be beneficial.
- Arrow panels had little effect on traffic operations in moving shoulder closures on freeways. Conflicts due to slow-moving vehicles were greater when the caution-bar mode was used.
- No differences were detected in the effect of various arrow panel modes such as the flashing arrow or sequential chevron. The MUTCD (*4*) states that arrow panels should "not be used to indicate a lane shift." Additionally, a separate arrow panel should be used for each closed lane in a multilane closure.

Wooldridge et al. (*1*) made the following recommendations based on a field test conducted to examine requirements for panel luminance intensity:

- Minimum nighttime on-axis intensity of 150 cd/lamp luminance
- Minimum nighttime off-axis intensity of 30 cd/lamp luminance
- Minimum daytime on-axis intensity of 500 cd/lamp luminance
- Minimum daytime off-axis intensity of 100 cd/lamp luminance
- If arrow panels are located on curves, orient them to be seen by a vehicle 1500 ft upstream.
- Realign the arrow panel to be perpendicular to the driver's line of sight at the distance desired for observation
- Minimum daytime on-axis intensity of 4000 cd/panel, minimum daytime off-axis intensity of 800 cd/panel, and maximum nighttime on-axis intensity of 5500 cd/panel

Design Issues

Field conditions such as fog or a high level of ambient light (advertising signs) might impact the visibility of the arrow panel in the field.

Mace, Finkle, and Pennak (*5*) note that the arrow panel should flash at a rate of 25 to 40 flashes per minute.

Cross References

Caution Mode Configuration for Arrow Panels, 13-6
Determining When to Use Decision Sight Distance, 5-8

Key References

1. Wooldridge, M.D., Finley, M., Denholm, J., Mace, D., and Patrick, B. (2001). *Photometric Requirements for Arrow Panels* (TX-02/4940-1). College Station: Texas A&M University.
2. Knapp, B., and Pain, R.F. (1979). Human factors considerations in arrow-board design and operation. *Transportation Research Record 703*, 1-8.
3. Graham, J.L., Migletz, J., and Glennon, J.C. (1978). *Guidelines for the Applications of Arrow Boards in Work Zones* (FHWA-RD-79-58). Washington, DC: FHWA.
4. FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD).* Washington, DC.
5. Mace, D., Finkle, M., and Pennack, S. (2001). *NCHRP Research Results Digest 259: Guidelines for the Effective Use and Procurement of Advanced Warning Arrow Panels*. Washington, DC: Transportation Research Board.

CAUTION MODE CONFIGURATION FOR ARROW PANELS

Introduction

This guideline provides recommendations for how to use the arrow panel *Caution Mode* configuration during temporary traffic control (*1*). The Caution Mode configuration is arrow panel mode C and provides flashing non-directional information. The purpose of the Caution Mode configuration is to increase safety near highway work zones by providing early warning information to drivers indicating that caution is required while approaching and traveling through the work zone. Note that these displays are only intended to alert drivers and to call attention to the appropriate signs, channelization devices, or other temporary traffic control devices that provide the actual information that drivers must use to safely navigate the work zone.

Design Guidelines

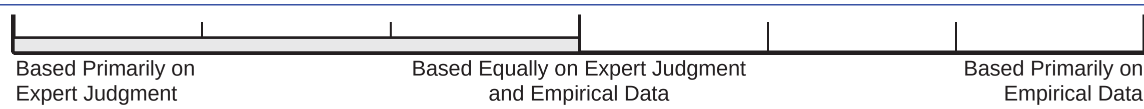
Caution Mode Usage

The MUTCD (*1*) states that the Caution Mode configuration should be used for the following situations:

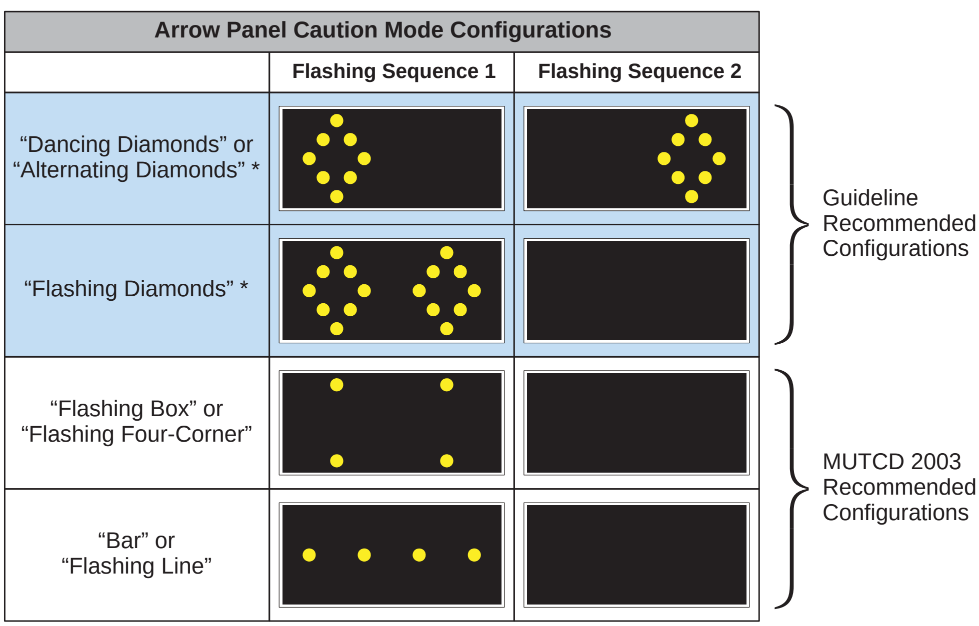
- Shoulder work
- Blocking of the shoulder
- Roadside work near the shoulder
- Temporary closing of one lane on a two-lane, two-way roadway

Caution Mode Display

Although the MUTCD states that Flashing Box or Flashing Line displays should be used, Alternating or Flashing Diamond displays are recommended over other displays because they are more attention getting and less confusing. Flash rates of 25 to 40 flashes/min should be used.



The figure below provides examples of different types of Cautionary Mode configurations for arrow panels (adapted from Saito and Turley (*2*).



* Use of this configuration may require the formal creation of an experimental project with FHWA.

Discussion

Caution Mode usage: The Caution Mode configuration should be used when directional information is not warranted (e.g., no merge is necessary), such as for shoulder work, blocking the shoulder, or roadside work near the shoulder (*1*). Some state DOTs also use the Caution Mode for slow-moving operations, such as street sweeping and striping (*3*). Note that the MUTCD (*1*) states that the Caution Mode is the *only* permissible usage of arrow panels when one lane must be closed on a two-lane, two-way street. Similarly, the Caution Mode should be used only if no lane change or merge is required. Consistent use of the Caution Mode in this situation helps drivers maintain a clear idea about how they should respond when seeing this display (and the same holds for arrow displays). If lane changes or merging is required on multi-lane roadways, then the arrow or chevron arrow-panel display must be used (*1*).

Caution Mode display: The diamond-based Caution Mode displays recommended in this guideline are different from the MUTCD recommended displays, and they are not MUTCD-compliant. However, the primary reasons for recommending these diamond displays is that they appear to lead to no worse performance than MUTCD-compliant displays, while at the same time providing a display that drivers find easier to see, more attention getting, and less confusing.

Two recent studies have compared the effects of diamond-based displays versus Flashing Box and Flashing Line displays on driver performance (*2*,*3*). Overall, Alternating Diamond displays lead to driver behavior that is not really different from that engendered by other display types in terms of lane migration, potential conflicts, and driver slowing (although diamond displays lead to a slightly greater degree of slowing with a statistically significant 2 mi/h reduction in mean speeds). These studies have also found important differences in driver opinions regarding the different display types (*2*,*3*). In particular, drivers rated the Alternating Diamond displays as easier to see, more attention getting, and less confusing than the other displays (*3*). Also, a Flashing Box display rated very poor in terms of prompting safe driving and was also rated as being much more likely to be ignored relative to Flashing and Alternating Diamond displays (*2*).

These findings are consistent with earlier research and opinions among highway researchers and administrators. For example, Knapp and Pain (*4*) found that more than 50% of drivers misinterpreted the meaning of Flashing Line and Flashing Box displays. Similarly, there is some broader concern that the Flashing Line display can be interpreted as a malfunctioning flashing arrow, resulting in unnecessary lane changes (*5*).

Finally, from a human factors perspective, the diamond displays should also be more salient and attention getting to drivers in potentially cluttered work zone environments because they are associated with a larger change of luminance (more lamps are illuminated).

Design Issues

There are no data currently available to suggest that either the flashing version or alternating version of the diamond displays is superior.

Flashing rate should be 25 to 40 flashes per minute.

Cross References

Procedures to Ensure Proper Arrow Panel Visibility, 13-4

Key References

1. FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD).* Washington, DC.
2. Saito, M., and Turley, B.M. (2002). *Dancing Diamonds in Highway Work Zones: An Evaluation of Arrow-Panel Caution Displays* (UT-02.13, Final Report). Provo, UT: Brigham Young University.
3. Griffith, A., and Lynde, M. (2001). *Evaluation of Arrow Panel Displays for Temporary Work Zones; Final Report* (FHWA-OR-RD-02-02). Salem: Oregon Department of Transportation.
4. Knapp, B., and Pain, R.F. (1979). Human factors considerations in arrow-board design and operation. *Transportation Research Record 703*, 1-8.
5. Noel, E.C., Sabra, Z.A., and Dudek, C.L. (1989). *Work Zone Traffic Management Synthesis: Selection and Application of Flashing Arrow Panels* (FHWA-TS-89-034). McLean, VA: FHWA. http://www.fhwa.dot.gov/tfhrc/safety/pubs/89034/89034.pdf

CHANGEABLE MESSAGE SIGNS

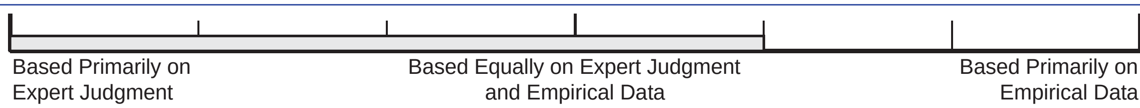
Introduction

Changeable message signs (CMSs) are electronic, reconfigurable signs placed above or near the roadway. They are used to inform motorists of specific conditions or situations. CMSs must communicate messages clearly in a brief period of time. Improper CMS usage defeats its credibility and can cause motorist confusion. Display messages ideally should be limited to a maximum of two phases. Many three-phase messages can be reduced to two or one phase by eliminating unnecessary wording. Other issues to avoid include splitting information across phases, using multiple formats of calendar dates, and displaying out-of-date information.

Design Guidelines

Fundamental human factors, identified mostly in Dudek (*1*), govern the use of CMSs. Some factors that should be considered follow.

Message Length and Format	Words should be simple and messages standardized. Abbreviations should be used only when easily understood.
The "Units" Rule	For road speeds > 35 mi/h, use a maximum of four units (one unit = one answer to one question). For examples, see revised message below. For road speeds ≤ 35 mi/h use a maximum of five units.
Device Consideration	CMSs should be placed so that approaching drivers see them 1500 ft or more upstream, and they are not overpowered by competing road or advertising signs or conditions.
Maximum Number of Words	Eight for 55 mi/h roads and seven for 65 mi/h roads.



Examples of how to revise a message to reduce reading time.

Message Element	Original Message	Revised Message
	Incident on Same Freeway as CMS Location	
Incident Descriptor	MAJOR ACCIDENT	FREEWAY BLOCKED (Unit 1)
Location	PAST I-80	PAST I-80 (Unit 2)
Lanes Affected	ALL LANES BLOCKED	
	Incident on Freeway Other than CMS Location	
Incident Descriptor	MAJOR ACCIDENT	I-76 WEST BLOCKED
Location	ON I-76 WEST AT WALT WHITMAN BRIDGE	AT WALT WHITMAN BRIDGE
Lanes Affected	ALL LANES BLOCKED	

Discussion

Message length and format: Because of the limited space on CMSs, suggestions for use are as follows:

- Messages should abbreviate the month in conjunction with the date.
- When future work will span days, the month should be noted only once in the message.

Other factors to consider include the following:

- Attempts to present day, date, and time information about upcoming roadwork appear to approach the limit of driver information processing.
- Regardless of the format used, only about two-thirds to three-quarters of the drivers viewing the portable changeable message sign (PCMS) will be able to correctly tell whether the work activity will affect their trip (*2*).

The "Units" rule: One unit of information equals one answer for one question. Research and operational experience indicate that no more than four units of information should be in a CMS when the traffic operating speeds are 35 mi/h or more. No more than five units of information should be displayed when the operating speeds are less than 35 mi/h. In addition, no more than three units of information should be displayed on a single message frame (*1*).

Because motorists can process only a limited amount of information at a given time, legibility and distance must be kept in mind. Based on the known legibility distance of CMSs, the calculated maximum message length that can be read by motorists is eight words for a traveling speed of 55 mi/h and seven words for a speed of 65 mi/h. A driver traveling at 60 mi/h is moving at 88 ft/s and can see a CMS for only 7.4 s at that speed (generally a CMS is legible for 650 ft) (*1*).

Device consideration: ITE's proposed equipment standard states that each PCMS unit shall be self-contained and consist of a message board, controller, power supply, electric cable, and adjustable height structural support system. The PCMS shall be suitable for either moving on a truck or two-wheeled trailer (*3*). The MUTCD (*4*) states that PCMSs mounted on trailers or large trucks should have a minimum letter height of 450 mm (18 in.). CMSs mounted on service patrol trucks should have a minimum height of 250 mm (10 in.). Each character should consist of a matrix at least five pixels wide and seven pixels high. The color of the elements should be yellow or orange on a black background. In addition, research suggests the following guidelines for CMS use:

- Device format should permit maximum amount of information display at a glance.
- CMS devices should be located 0.75 mi in advance of closure.
- CMS devices are to be considered supplemental to currently applied standard traffic control device schemes.
- CMS devices are not to be considered as an alternative to the arrow panel (*5*).

Design Issues

None.

Cross References

Sign Legibility, 13-10

Key References

1. Dudek, C. (2002). Guidelines for changeable message sign messages. Presentation at theTMC Pooled-Fund Study Annual Meeting, Arlington, VA. Retrieved on July 21, 2006, from http://tmcpfs.ops.fhwa.dot.gov/meetings/mtg_detail.cfm?id=10
2. Ullman, G.L., Ullman, B.R, Dudek, C.L, Williams, A., and Pesti, G. (2005). *Advanced Notification Messages and Use of Sequential Portable Changeable Message Signs in Work Zones*. College Station, Texas A&M University.
3. ITE (1988). Portable bulb-type changeable message signs for highway work zones: Proposed equipment standard. *ITE Journal, 58*(4), 17-20.
4. FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD).* Washington, DC.
5. Hanscom, F.R. (1982). Effectiveness of Changeable Message Signing at Freeway Construction Site Lane Closures. *Transportation Research Record, 844*, 35-41.

SIGN LEGIBILITY

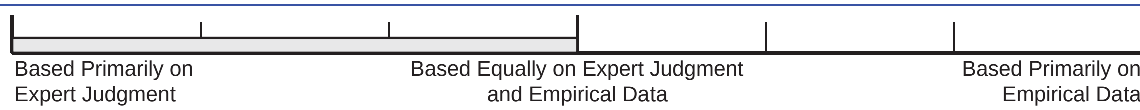
Introduction

Sign legibility refers to specific design characteristics of work zone signs that contribute to drivers' ability to perceive and understand the sign's message. A number of factors determine the legibility of work zone signs including retroreflectivity (sheeting type), color, letter font, and location of sign (roadside or overhead). The legibility index of various sign sheeting can be used to ensure designs that can accommodate all drivers regardless of age and light conditions. Prismatic sheeting ensures greater retroreflectivity of work zone signs and the addition of fluorescent colors improves the sign conspicuity in daytime low-light conditions such as dusk, dawn, or fog conditions.

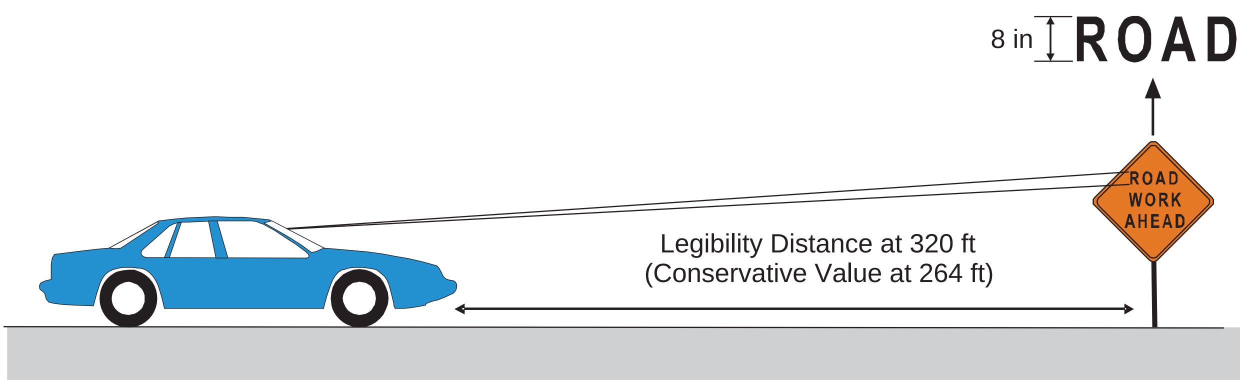
Design Guidelines

Studies conducted in Texas (*1*) have the following findings:

Color	Overall, yellow and white backgrounds on signs provide the greatest legibility distances followed by green and then orange backgrounds. The MUTCD requires the use of an orange background and black letters in work zone signs (*2*).
Retroreflectivity (Sheeting Type)	Fluorescent microprismatic sheeting with orange background provide for greater legibility distance than high-intensity sheeting.
Letter Height	A maximum legibility index of 40 ft of distance/in. of letter height should be used; a more conservative value is 33 ft/in, which is especially good for older drivers.



The figure below describes legibility distance for work zone signs.



Discussion

Retroreflectivity: A report by the Virginia Transportation Council has specified that for a prismatic lens retroreflective sheeting material, the specification should include values for the material's orientation and rotation angles, in addition to its entrance and observation angles (*3*). For high-speed (usually greater than 50 mi/h) highways, anywhere a critical vehicle maneuver is necessary, and in areas of high to medium visual complexity, higher values of sign luminance are required for safety (*4*). Another report finds that for existing traffic control devices, the beneficial effects of upgrading the type of sheeting used on barrels, barricades, and vertical panels were demonstrated by increased detection and recognition distances. However, the super-engineering grade offered the most cost-effective and balanced solution for upgrading sheeting (*5*).

Legibility: A study has recommended the use of work zone signs with orange background, micro-prismatic materials, which provide far greater legibility distance than high-intensity ones (*6*). Micro-prismatic fluorescent orange materials were found to perform better than Type 3 (*1*).

Color: Speed variances tended to decrease at the midpoint and the taper with fluorescent signs relative to standard orange signs. The collision reduction in the overall traffic conflicts from what was expected at all treatment sites was about 7% (*6*).

Design Issues

Height of letters used depends on site characteristics such as operating speed (*1*).

Cross References

None.

Key References

1. Chrysler, S.T., Carlson, P.J., and Hawkins, H.G. (2003). Nighttime legibility of traffic signs as a function of font, color, and retroreflective sheeting. *Transportation Research Board 82nd Annual Meeting Compendium of Papers* [CD-ROM].

2 FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD).* Washington, DC.

3. Brich, S.C. (2002). *A Determination of the Appropriateness of Virginia's Retroreflective Sign Sheeting Specification for Fluorescent Orange Construction and Maintenance Signs.* Final Report (FHWA/VTRC 03-R5). Charlottesville: Virginia Transportation Research Council.

4. Russell, E.R., and Rys, M. (1992). *A Review of Kansas Department of Transportation's Reflective Sheeting Policy.* Final Report. Manhattan: Kansas State University.

5. Ahmed, S.A. (1991). *Evaluation of Retroreflective Sheetings for Use on Traffic Control Devices at Construction Work Zones.* Final Report. Stillwater: Oklahoma State University.

6. Hummer, J.E., and Scheffler, C.R. (1999). Driver performance comparison of fluorescent orange to standard orange work zone traffic signs. *Transportation Research Record, 1657,* 55-62.

DETERMINING WORK ZONE SPEED LIMITS

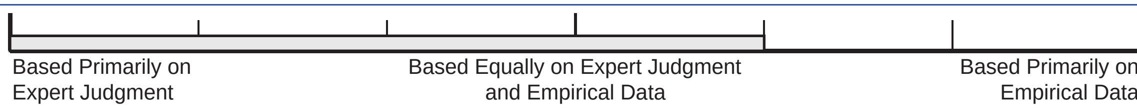
Introduction

Work zone speed limits refer to the reduced speed limits used in work zones to maintain safe traffic flow. Vehicle speeds in work zones are influenced by the geometrics of the roadway and the location of various work zone features such as lane closure tapers and work activity. Work zone speed limits within 10 mi/h of normal speed limits have more credibility and have been proven to be safer than speed limits that are 15 to 30 mi/h below the normal speed limit.

Design Guidelines

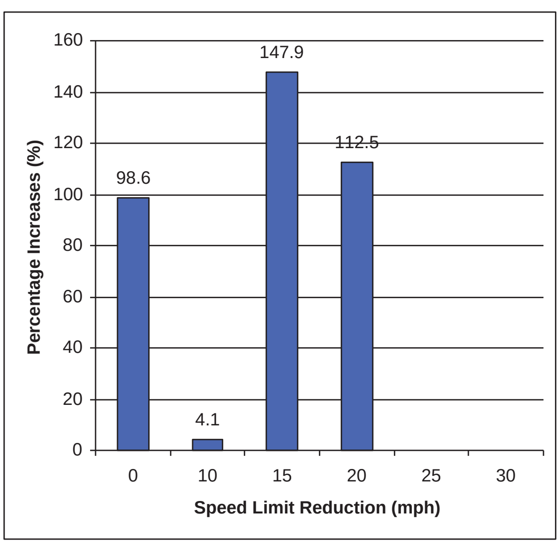
Speed and crash studies confirm that large speed limit reductions in work zones are undesirable (*1*). Speed limit reductions to 10 mi/h below the preconstruction speed limit resulted in the smallest increase in speed variance with the work zone—relative to the speed variance upstream of the work zone—of any of the speed limit strategies studied. Additionally, in rural freeway work zones involving work on or near the traveled way, a 10 mi/h reduction in the work zone speed limit minimized the crash rate increase from the preconstruction period to the construction period.

Speed Reductions and Speed Limit	A study has found that mean vehicle speed reductions were the greatest in work zones where the speed limit was not reduced, or at least not reduced more than 10 mi/h. Speed limits need to be reduced only in the direction of traffic affected by the work zone when a wide median is between the directions of flow.
Lane Widths and Number of Lanes	Observed or achieved mean vehicle speed reduction appears to be highly correlated with the number of open lanes and lane widths.
Speed Display	CMSs with radar were successful in causing speeders to slow down in work zones. However, use of work zone speed limit signs with flash beacons produced mixed results.

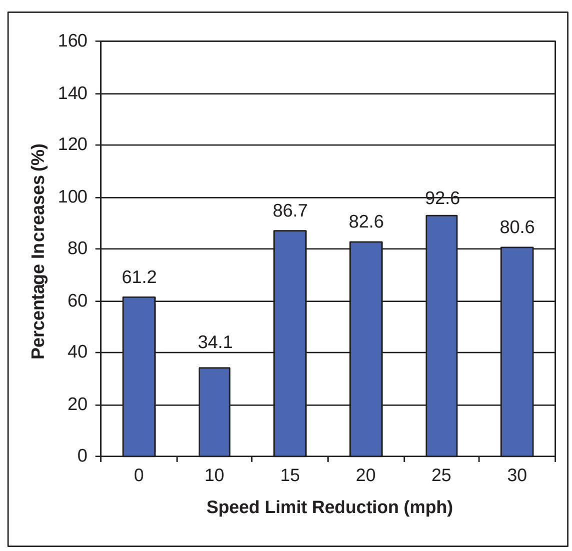


Speed considerations in work zones

Increase in fatal plus injury crash rates from before construction to during construction.



Increase in speed variance from upstream of work zone to work zone.



Discussion

Speed reductions and speed limit: Studies have found that speed limit compliance decreased when the speed limit was reduced by more than 10 mi/h. Mean speeds were approximately 5 mi/h lower within work zones with no speed limit reduction than they were upstream of the same work zones. Speed limit compliance was found to be the greatest in work zones where the speed limit was not reduced (*1*). Another study noted that the mean and 85th percentile speeds were approximately 9 mi/h lower within the work zones of speed limit reductions of 10 mi/h than upstream of those same work zones and showed that the entire traffic stream uniformly reduced speeds (*2*). In general, speed reduction is better achieved when the work zone is well marked in advance of the work zone activity; motorists slow down out of self preservation and not the speed limit. Note that people drive the speed they feel comfortable with regardless of the posted speed limit if enforcement is not present (*3*), whereas speed reduction as high as 9.1 mi/h was observed with the presence of police (*4*).

Lane widths and number of lanes: Lane widths are directly related to speed reduction on roadways. For 11-ft lanes, speed reduction of 4.4 mi/h was observed to be 133% more than the value of 1.9 mi/h recommended by the *Highway Capacity Manual* (HCM) (*5*) for basic freeways. For 10.5-ft lanes, the observed reduction of 7.2 mi/h was 69% greater than the value of 4.25 mi/h recommended by the HCM (*6*). In addition, speed reduction appears to be highly correlated with the number of open lanes. Motorists tend to select higher speeds, regardless of the posted work zone speed limit, when more lanes are open to traffic (*7*).

Speed display: CMSs with radar were successful in effecting significant speed reduction in work zones. Also, no significant differences were found to exist in the speed reductions between vehicle types (*8*). However, another study found that the use of work zone speed limit signs with flashing beacons produced mixed results. Speed reductions were insignificant on urban arterials where commercial advertisements and other traffic control devices compete for drivers' attention (*9*).

Design Issues

A work zone speed limit may also be affected by restrictive geometric features such as curves or intersections.

Cross References

Influence of Speed on Sight Distance, 5-12

Key References

1. Migletz, J., Graham, J., Hess, B., Anderson, I., Harwood, D., and Bauer, K. (1998). *Effectiveness and Implementability of Procedures for Setting Work Zone Speed Limits.* Final Report, NCHRP Project 3-41(2). Independence, MO: Graham–Migletz Enterprises.
2. Sisiopiku, V.P., Lyles, R.W., Krunz, M., Yang, Q., Akin, D., and Abbasi, M. (1999). *Study of Speed Patterns in Work Zones*. East Lansing: Michigan State University.
3. Fors, C. (2000). Work zone ahead: reduce speed. *Roads and Bridges, 38*(1), 58-61.
4. Lyles, R.W., and Sisiopiku, V.P. (1999). *An Evaluation of Speed Control Techniques in Work Zones (Work Zones 2)*. East Lansing: Michigan State University.
5. Transportation Research Board (2010). *Highway Capacity Manual 2010.* Washington, DC.
6. Chitturi, M.V., and Benekohal, R.F. (2005). Effect of lane width on speeds of cars and heavy vehicles in work zones. *Transportation Research Record, 1920,* 41-48.
7. Sawaya, O.B., and Schofer, J.L. (2000). Speed up, or slow down. *World Highways/Routes Du Monde, 9*(6), 78-79.
8. Fontaine, M.D., and Garber, N.J. (1996). *Controlling Vehicle Speeds in Work Zones: Effectiveness of Changeable Message Signs With Radar* (UVA/529242/CE96/102). Charlottesville: University of Virginia.
9. Hall, J., and Wrage, E. (1997). *Controlling Vehicle Speeds in Highway Construction Zones* (NMSHTD-97-07). Albuquerque: University of New Mexico.

CHAPTER 14

Rail-Highway Grade Crossings

TASK ANALYSIS OF RAIL-HIGHWAY GRADE CROSSINGS

Introduction

This guideline addresses the key factors found to affect driver decisions regarding whether to obey traffic control devices at rail-highway grade crossings. Most crossings have traffic control devices (TCDs) installed and yet vehicle-train crashes still occur. From 1998 to 2007, 24,609 crashes occurred at public crossings that had warning devices installed (*1*). One reason that crashes occur is that individual factors cause drivers to disregard traffic control devices and put themselves into situations where there is a conflict risk. Although these factors are unique to each driver, the information provided by the crossing warnings can support safe decision-making.

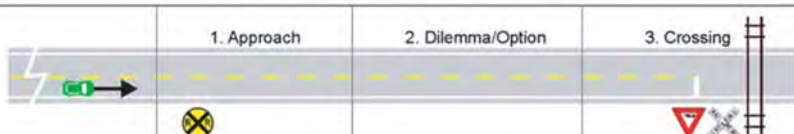
Design Guidelines

The following table provides information and guidelines for addressing factors that affect compliance with traffic control devices at rail-highway grade crossings. The following guidelines should be considered in order to improve stopping/yielding behavior and reduce vehicle-train crashes.

Factor	Compliance Issue	Guideline
Driver	Familiarity	Consider active devices if warranted.
	Expectations	Alert drivers that the crossing is operational (if it is).
	Credibility	Only use active warning devices in environments where they can provide warnings of a predictable, constant length.
	Reliability	Use reliable warning devices.
TCD Design/ Roadway	TCD timing	Balance active warning timing so that it is long enough to provide enough time for drivers to make a go/no-go response, but not so long as to decrease compliance. → Guideline: Timing of Active TCDs at Rail-Highway Grade Crossings (p. 14-6)
	TCD selection	TCD selection should support the time available for the driver to make a go/no-go decision given the sight lines at the crossing. →Guideline: Human Factors Considerations in TCD Selection at Rail-Highway Grade Crossings (p. 14-12)
	Train speed perception	When drivers must judge the speed of an approaching train head-on (as from a Stop Sign at the crossing), train speed perception cues should be provided. →Guideline: Human Factors Considerations in TCD Selection at Rail-Highway Grade Crossings (p. 14-12)
	Sight lines	Support driver decision-making by providing sight lines consistent with the requirements of the TCD. →Guideline: Human Factors Considerations in TCD Selection at Rail-Highway Grade Crossings (p. 14-12)

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

TASK ANALYSIS FOR RAIL-HIGHWAY GRADE CROSSINGS



	1. Approach	2. Dilemma/Option	3. Crossing
Key Driving Tasks *	• View crossing • Look for train/ stopped vehicles • View TCD status	• Choose safe and legal action (go/no-go) • Adjust speed • Monitor train presence • Monitor TCD status	• Monitor for hazards • Cross track(s) • Adjust speed for roadway beyond
Visual Information Sources	• Advance signage • Other vehicles • Train • TCD	• TCD • Train location relative to roadway and estimated speed	• Track geometry • Hazards: multiple tracks, side rails, pedestrians, etc.
Internal Compliance Factors	• Driver familiarity • Driver expectations	• TCD credibility • TCD reliability	NA
External Compliance Factors	• Sight distance	• Train speed perception • TCD selection • TCD timing	• TCD timing

* Key driving tasks may not happen in the order listed and some may be performed simultaneously.

Discussion

Many of the driver factors that are incorporated into this guideline are covered in more detail in subsequent guidelines. It is important to consider these factors when planning a crossing because ultimately drivers decide whether they will comply with a warning device.

Familiarity: Abraham, Datta, and Datta (*2*) observed vehicles at train crossings and mailed surveys to the violators. They found that, of the drivers who violated the warning device, 68% traversed the specific crossing at least four times per week and 19% crossed two to four times per week.

Expectations: Raslear (*3*) performed an analysis of train detection at rail crossings using signal detection theory and compared the results to those found using crash data. Both analyses confirmed that if drivers expected to see a train at the crossing (and/or trains passed through more frequently), they were less likely to get in an accident.

Credibility: The level of trust that a driver has in the timing of the warning device is affected by the length of time that the driver has to wait, and the consistency of this time. Generally, as the warning time increases, the number of violations increases (*4*). Drivers expect a train to arrive within a certain amount of time after the activation of the warning devices. Additionally, constant warning-time systems (rather than fixed-distance systems) have been shown to decrease mean warning times and increase compliance (*4*).

Reliability: Reliability is characterized by the accuracy with which an active warning device indicates that a train is approaching every time a train is coming and only when a train is coming. Gil, Multer, and Yeh (*5*) used a simulator to test participant responses at a crossing with a single-quadrant automatic gate, after participants were primed on the reliability of the traffic control device. Gil et al. found that as the probability that a warning device actually indicated the presence of a train decreased, the frequency of gate violations increased (*5*). Although in the simulator, participants were biased towards proceeding regardless of the warning reliability (perhaps due to time-based completion incentives), indicating the possibility of the influence of other motivational factors.

Design Issues

Gate-rushing is a specific type of violation that has been observed where drivers drive around gates that are closed or gates that are in the process of closing when trains are near the rail-highway grade crossing (*6*). There is no indication as to why drivers choose such a risky maneuver; they may be in a hurry, think they have enough time to pass, or have found the gate to be unreliable in the past. This behavior may be explained by some of the driver factors described in this guideline, or it may be related to other additional factors. Countermeasures regarding gate-rushing are discussed in "Countermeasures to Reduce Gate-Rushing at Crossings with Two-Quadrant Gates" on page 14-10.

The degree to which the driver holds the train operator accountable for the driver's crossing safety also affects crossing compliance (*7*). Drivers tend to think that train operators share some of the responsibility for crossing safety, i.e., if a driver and the train reach the crossing at the same time, the driver assumes that there is a shared responsibility for collision avoidance.

Advisory speed signs can be confusing to drivers if they are unaware of the reason for the reduced speed.

Cross References

Rail-Highway Grade Crossings Guidelines, 14-1

Key References

1. Raub, R.A. (2009). Examination of highway-rail grade crossing collisions nationally from 1998 to 2007. *Transportation Research Record, 2122*, 63-71.
2. Abraham, J., Datta, T.K., & Datta, S. (1998). Driver behavior at rail-highway crossings. *Transportation Research Record, 1648*, 28-34.
3. Raslear, T.G. (1995). Driver behavior at rail-highway grade crossings: A signal detection theory analysis. In A.A. Carroll & J.L. Helser (Eds.). *Safety of Highway-Railroad Grade Crossing. Research Needs Workshop. Volume II - Appendices* (DOT/FRA/ORD-95/14.2p. 46 p.). Washington, DC: U.S. Department of Transportation.
4. Yeh, M., & Multer, J. (2007). Traffic control devices and barrier systems at grade crossings: Literature review. *Transportation Research Record, 2030*, 69-75.
5. Gil, M., Multer, J., & Yeh, M. (2007). *Effects of Active Warning Reliability on Motorist Compliance at Highway-Railroad Grade Crossings* (DOT-VNTSC-FRA-09-04. DOT/FRA/ORD-09-06). Washington, DC: Federal Railroad Administration.
6. Khattak, A.J., & McKnight, G.A. (2008). Gate rushing at highway-railroad grade crossings: Drivers' response to centerline barrier. *Transportation Research Record, 2056*, 104-109.
7. Richards, S.H., & Heathington, K.W. (1988). Motorist understanding of railroad-highway grade crossing traffic control devices and associated traffic laws. *Transportation Research Record, 1160*, 52-59.

DRIVER INFORMATION NEEDS AT PASSIVE RAIL-HIGHWAY GRADE CROSSINGS

Introduction

This guideline refers to the information that drivers need to behave safely at rail-highway grade crossings that are protected by passive devices. This is especially relevant for crossings with only passive protection since drivers carry the full responsibility of determining if a train is approaching. In the past, crossings have been marked by crossbucks alone; however, the crossbuck is now required to be accompanied by a Yield or Stop sign (*1*). Yield and Stop signs address many of the deficiencies of crossbucks by more directly and effectively fulfilling driver information needs.

Design Guidelines

This guideline provides recommendations regarding the type of information that should be presented at rail-highway grade crossings protected by passive warning devices.

If the rail-highway grade crossing is protected by passive warning devices, verify the following information (2):

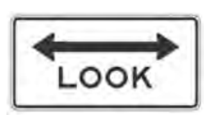
A. Existence of a rail-grade crossing ahead.
B. Passive status of the crossing, so it is the driver's responsibility to determine if a train is at or near the crossing.
C. Actions that are required of the driver (e.g., maintain speed, slow down, look for trains).
D. If there are special conditions that require more driver attention (e.g., limited sight distance, skewed crossing).

The following signs and plaques provide information to help meet some of the driver information needs listed above. These signs and plaques are presented in addition to traditional Stop and Yield signs, as discussed on the following page. The signs are labeled as they are in the 2009 MUTCD and include the information need(s) that they satisfy in parentheses.

EXAMPLES OF PASSIVE SIGNING TO FULFILL DRIVER INFORMATION NEEDS (NOT TO SCALE)

W10-1 (A)

W10-13P (B)



R15-8 (B, C)

W10-15P (D)

W10-12 (D)

R15-2P (D)

W10-9P (D)

Source: FHWA (*1*)

Discussion

The information needs described in the guideline on the previous page are not adequately addressed by crossbuck warning devices alone. The signs and plaques provided are examples of countermeasures that can be used to fill some of these needs. However, the effectiveness of the various signs in improving driver safety is unknown. An additional, required sign element at passive crossings is the Yield or Stop sign. The following table shows ways in which Yield and Stop signs address the deficiencies of crossbucks in providing information needs (adapted from Lerner, Llaneras, McGee, and Stephens (*2*)). The information needs are labeled as listed in the table on the previous page.

Information Need	Crossbuck Deficiency	Yield or Stop Sign Mitigation
A. Existence of rail-grade crossing ahead	Lacks conspicuity.	Yield (or Stop) adds red color, greater retroreflective surface area, and icons with high target value.
	Ineffective for non-English-literate drivers.	Well-understood icons for Yield and Stop.
	Unclear indication of the point of intersection between the roadway and track.	Understood that Yield (or Stop) is located at the intersection.
B. Passive status of the crossing, so the driver has the responsibility to look for a train	Fails to distinguish driver requirements for active vs. passive crossings.	Presence of Yield (or Stop) indicates passive crossing.
	Difficult to distinguish active vs. passive crossings on approach.	Well-understood distinct advance signs for Yield and Stop.
	Lack of a clear indication of need and responsibility to search.	Yield is understood to mean search for conflicting vehicles.
C. Actions that are required of the driver.	Fails to induce appropriate slowing.	Yield is understood to require slowing.
	Poor comprehension of regulatory meaning of crossbuck.	Meaning of Yield (or Stop) is well understood.
	Stop-look-listen fallacy.	Clearly distinguishes when mandatory stop is required; Yield does not imply stop.
D. Special conditions that warrant attention.	Coping with special demands, unusual features.	Advance signing for hazards, under well-defined conditions of presentation.

It is evident that Yield and Stop signs address the driver's information needs more thoroughly than crossbucks alone. Lerner et al. (*2*) suggests the use of a Yield sign unless a Stop sign is warranted to reduce the likelihood of train-vehicle conflicts. To fulfill the objective of providing clear guidance to drivers, Lerner et al. (*2*) supports the use of two additional plaques to be displayed below the existing Grade Crossing Advance Warning Signs. These plaques would convey the status of the upcoming warning devices, either active or passive. The passive plaque reads "No Signals or Gates," while the active plaque shows an icon of a flashing-light signal with the words "Signal Ahead." The addition of the new plaques would provide information to drivers regarding the status of the upcoming traffic control devices on the approach to the crossing. The current MUTCD has a similar passive warning plaque (W10-13P), which is optional, but does not support the active plaque.

Design Issues

Olson, Dewar, and Farber (*3*) include another list of driver information needs: (1) something is there, (2) the item that the driver sees is a train, (3) the train will cross the road that the driver is on, (4) the distance to the train, and (5) the train's speed and direction. These needs would likely be difficult to meet using passive signage. However, they highlight the significance of environmental contextual cues as an addition to engineering countermeasures to help the driver interpret their surroundings. These driver information needs also highlight the limitations of Yield signs, especially under ambiguous circumstances.

Cross References

Human Factors Considerations in Traffic Control Device Selection at Rail-Highway Grade Crossings, 14-12

Key References

1. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways.* Washington, DC.
2 Lerner, N.D., Llaneras, R.E., McGee, H.W., & Stephens, D.E. (2002). *NCHRP Report 470: Traffic-Control Devices for Passive Railroad-Highway Grade Crossings.* Washington, DC: Transportation Research Board.
3. Olson, P.L., Dewar, R., & Farber, E. (2009). *Forensic Aspects of Driver Perception and Response.* Tuscon, AZ: Lawyers & Judges.

TIMING OF ACTIVE TRAFFIC CONTROL DEVICES AT RAIL-HIGHWAY GRADE CROSSINGS

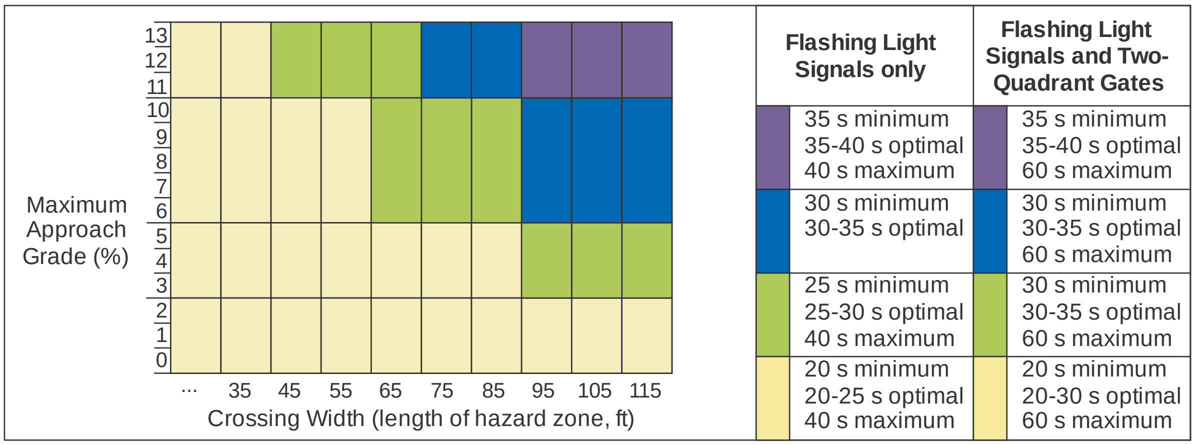
Introduction

This guideline refers to the *warning time*, or the time between the initiation of the flashing light traffic control devices and the arrival of the train. If the total warning time or portions of the timing are too short, drivers are at a risk of not being able either to stop in time for the gates to descend or to pass over the crossing from the dilemma zone. On the other hand, if the warning time is too long, drivers are less likely to comply with the warning devices (*1*).

Design Guidelines

The following graph of active traffic control device timings should provide adequate time for drivers to stop or to cross when appropriate (adapted from *1*).

WARNING TIMES FOR RAIL-HIGHWAY GRADE CROSSINGS

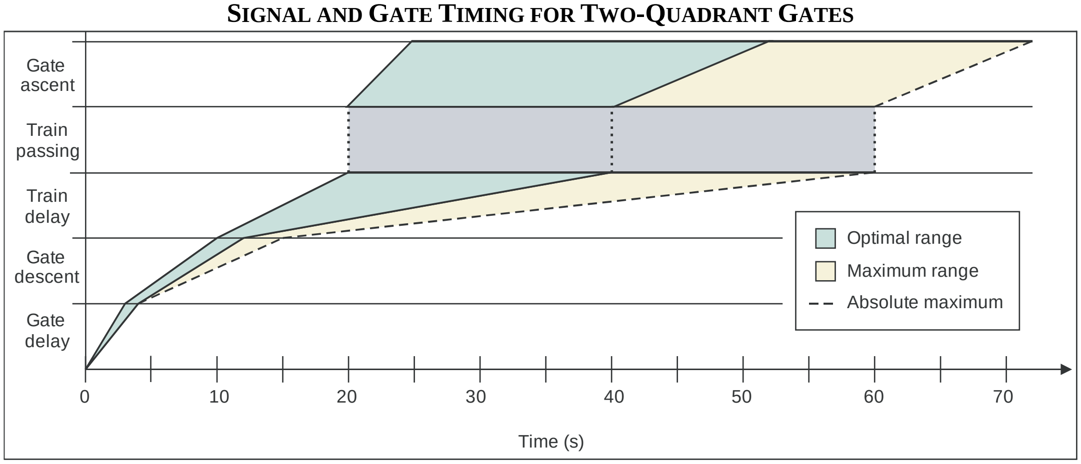


- If twin or triple tractor-trailer combinations are expected, increase the minimum and optimal times by 10%.
- If more than 10% of the warning times exceed the maximum times, motion sensors or train predictors should be installed to reduce warning times. Gates should be considered for flashing light crossings and four-quadrant gates should be considered for two-quadrant enforced crossings.
- All of the warning times for crossings with gates include gate delay/descent time.

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

The graphic below shows in more detail the recommended signal and gate timing for two-quadrant gates.

SIGNAL AND GATE TIMING FOR TWO-QUADRANT GATES



Source: Richards & Heathington (*1*), FHWA (*2*)

Discussion

Warning times: Richards and Heathington (*1*) conducted field observations and a laboratory study to determine the expectations of drivers for warning times at rail-highway grade crossings. Driver observations were made using video tape at three crossings that had relatively high volumes of train and vehicle traffic as well as some past accidents. The crossings had flashing light signals or flashing light signals and standard gates. At the crossings with only flashing light signals, most drivers crossed without stopping if they arrived within 1 s of the warning period beginning. This proportion steadily decreased and leveled off around 4 s, when most drivers stopped. However, at the crossings with both gates and flashing light signals, most drivers did not react to the light activation and tried to beat the gate. More than 60% of the drivers crossed without stopping 9 s into the warning period. The percentage of drivers who stopped only leveled off when they could no longer beat the gates. The total warning time is composed of the gate delay, gate descent, and train delay times (for crossings with gates).

Gate delay and gate descent: The gate delay is defined as the length of time between the start of the flashing lights and the initiation of the descent of the entry gate (*3*). The percentage of drivers who cross without stopping increases with increasing gate delay/descent time (*1*). As the combined time increased from 10-14 s, the percentage of drivers who did not stop increased dramatically to level off at around 50% at a 15-s combined time. Thus, the authors recommend that the combined gate delay and descent period should optimally be between 10 s and 12 s, with an absolute maximum of 15 s. The MUTCD (*2*) requires that the gate arm start its descent at least 3 s after the start of the flashing lights. Richards and Heathington (*1*) give an upper limit of 4 s to this value, except when vehicle approach speeds exceed 60 mi/h.

Train delay: The train delay is the amount of time between the gate descent and the train arrival. At the crossings with only flashing light signals, 98% of drivers stopped and remained stopped for warning times of 20-25 s, 73% for times of 25-30 s, and 90% for times of 30-35 s. Beyond 35 s, driver stopping behavior declined rapidly and when warning times exceeded 80 s, less than 20% of drivers stopped. At the gated crossing, 90% of drivers stopped and remained stopped for warning times of 20-25 s, 70% for times of 25-30 s, and 60% for times of 30-35 s. Beyond 35 s, the percentage stopped remained constant around 60%, with a sharp drop after 80 s. At the crossing with only flashing light signals but no predictors, generally long warning times led to compliance percentages below 30% for all warning times. Even when the warning times matched those at signalized crossings with predictors, compliance was much lower, perhaps due to a holdover effect that long and variable warning times have on general driver behavior at specific crossings.

Within this warning time, the MUTCD (*2*) requires that the gate arm reach a horizontal position at least 5 s before the train arrives at the crossing and remain down for the duration of the time that the train is at the crossing. Additionally, the MUTCD provides the standard that flashing-light signals should operate for at least 20 s before the arrival of a train under most circumstances. In a follow-up laboratory study (*1*), drivers viewed videos of train crossings and noted when they expected the train to arrive and when the elapsed time without a train arrival had become too long. When comparing flashing-light-only crossings to those with gates, the expected train arrival times are approximately the same (14.5 s to 13.2 s) when gate delay and descent are not included. The mean train delay to be considered excessive was 66.2 s for the gated crossing (including gate delay and descent) and 48.8 s without gate delay and descent times. This time was significantly longer than that for the flashing-light-only crossing at which a 39.7-s delay was considered excessive.

Gate ascent: The MUTCD (*2*) provides the guidance that the gate arm should ascend to the vertical position in 12 s or less after the train clears the crossing (if no other train traffic is detected). After the gate arm ascends, the flashing light signals and lights on the gate arms should extinguish.

Design Issues

A caveat of this research is that few observations occurred when large vehicles were present. The times presented are based upon driver behavior rather than stopping distance calculations, which vary based on vehicle size. Also, only one gated crossing was included in the study done by Richards and Heathington (*1*).

Cross References

Task Analysis of Rail-Highway Grade Crossings, 14-2
Human Factors Considerations in Traffic Control Device Selection at Rail-Highway Grade Crossings, 14-12

Key References

1. Richards, S.H. & Heathington, K.W. (1990). Assessment of warning time needs at railroad-highway grade crossings with active traffic control. *Transportation Research Record, 1254,* 78-84.
2. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
3. Coleman, F., III. & Moon, Y.J. (1996). Design of gate delay and gate interval time for four-quadrant gate system at railroad-highway grade crossings. *Transportation Research Record, 1553,* 124-131.

FOUR-QUADRANT GATE TIMING AT RAIL-HIGHWAY GRADE CROSSINGS

Introduction

This guideline refers to the *gate interval time*, which is the length of time between the initiation of the descent of the entry gate and the initiation of the descent of the exit gate at a crossing with a four-quadrant gate device (*1*). The gate interval needs to be long enough to allow even large vehicles to finish passing over the crossing before the second gate closes, but not so long that vehicles will try to bypass the first gate to beat the train through the crossing.

Design Guidelines

The following equations can be used to calculate gate delay and gate interval times at four-quadrant gates (*1*).

Gate operation time = Gate delay + Gate interval time

$$Gate\ delay\ (s) = \left[t + \frac{v}{2(a + G \cdot g)} + \frac{D}{v}\right]$$

$$Gate\ interval\ time\ (s) = \left[\frac{1}{v}(W_{ght} + L)\right]$$

Where:

- t = driver perception-reaction time (PRT, s)
- v = approach speed (m/s)
- a = deceleration level on level pavement (m/s^2)
- G = acceleration resulting from gravity (m/s^2)
- g = grade of approach lanes (percent/100)
- D = distance between stop bar and gates (m)
- L = length of the vehicle (m)
- W_{ght} = distance between entry and exit gates (m); for calculation see below

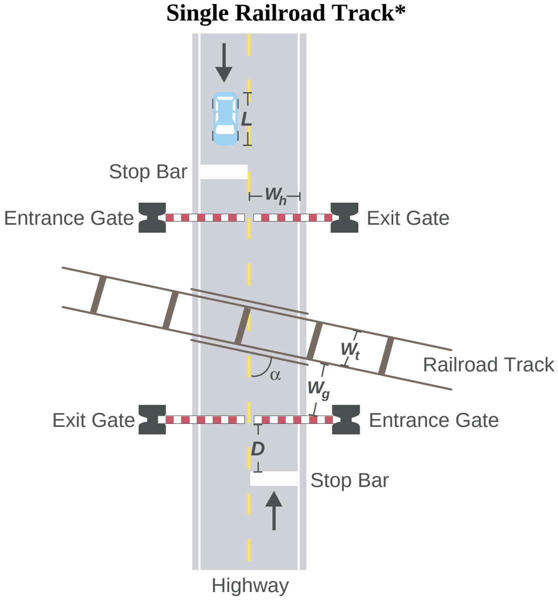
For α ≤ 90°: $$W_{ght} = \frac{W_t}{\sin\alpha} + \frac{2W_h}{\tan\alpha} + \frac{2W_g}{\sin\alpha}$$

For α > 90°: $$W_{ght} = \frac{W_t}{\sin(180-\alpha)} + \frac{2W_h}{\tan(180-\alpha)} + \frac{2W_g}{\sin(180-\alpha)}$$

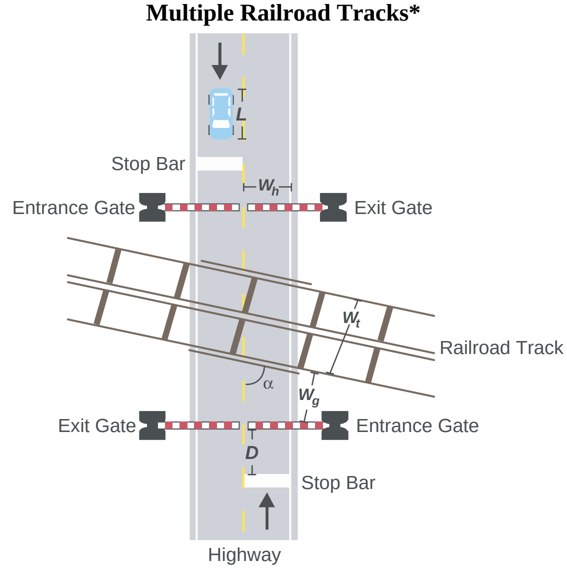
Where:

- W_{ght} = distance between entry and exit gates (m)
- W_t = width of railroad track (m)
- W_h = width of approaching lane of the highway (m)
- W_g = distance from track edge to gate (m)
- α = crossing angle (degrees)

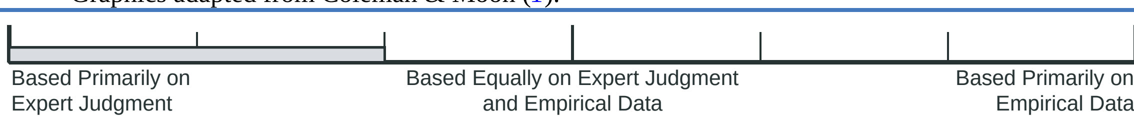
Single Railroad Track*



Multiple Railroad Tracks*



*Graphics adapted from Coleman & Moon (*1*).



Discussion

Four-quadrant gates are desirable for their ability to restrict through traffic at grade crossings. Four-quadrant gates are more effective at controlling gate-rushing, that is passing around gate arms that are already descended on two-quadrant gates (see "Countermeasures to Reduce Gate-Rushing at Crossings with Two-Quadrant Gates" on page 14-10). The MUTCD (*2*) guidance suggests that four-quadrant gate systems should only be used at crossings that are equipped with constant warning time detection. A critical operational element of such systems is the operation of the exit gate arm. The exit gate arm must be timed in such a way that it is still effective against drivers attempting to drive in the opposing direction around the entry gate, yet it does not trap vehicles trying to clear the crossing in the proper lane between the two gate arms. The MUTCD (*2*) defines the *exit gate clearance time* as "the amount of time provided to delay the descent of the exit gate arm(s) after entrance gate arm(s) begin to descend," equivalent to the *gate interval time* in this guideline. The MUTCD (*2*) also describes two operating modes for the exit gate arms. The Timed Exit Gate Operating Mode has a predetermined gate interval time, while The Dynamic Exit Gate Operating Mode bases the gate operation on the presence of vehicles within the minimum track clearance area. For either operating mode, the exit gate clearance time, or gate interval time, should be considered when determining the warning time. The timing guidance provided by the MUTCD (*2*) states that the gate arms blocking the entrance lanes should begin their descent no less than 3 s after the flashing lights begin flashing and reach the down position no less than 5 s before the train arrives. Exit arm timing should be based upon detection or timing requirements as determined by an engineering study.

The design of this timing concept is based on the concept of the dilemma zone, similar to that at signalized intersections (*1*). When the flashing signal lights begin flashing at a grade crossing, the driver must decide if he/she needs to stop or can proceed through the crossing before the gates descend. There are three relevant distances involved in the decision: the distance between the driver and the crossing, the distance that the vehicle travels prior to the descent of the entry gates (continuation distance), and the stopping distance before the crossing. If the stopping distance and continuation distance are equal, the driver is at a "safe decision location" where he/she may either stop or clear the crossing safely. This location is used to simplify the model. Although this model is based upon a single study, the methodology was validated using six crossings under consideration for four-quadrant gates.

Coleman and Moon (*1*) use perception-reaction times (t) of 1.0 s and 2.5 s in the model. Additionally, they cite a deceleration level (a) of 3.04 m/s^2 as found in intersection studies with approach speeds of 35 mi/h. The MUTCD guide states that, where possible, a safety zone able to accommodate at least one design vehicle should exist between the exit gate and the nearest rail (distance W_g in this guideline).

Design Issues

A *dynamic dilemma zone* has been defined in reference to intersections as "a road segment on approach to an intersection which varies in length based on fluctuations in vehicle speeds and the number of vehicles within a road segment" (*3*). The model is highly similar to the static dilemma zone model discussed in this guideline, but can account for vehicle accelerations/decelerations near the crossing and vehicle platoon behavior.

Cross References

Task Analysis of Rail-Highway Grade Crossings, 14-2
Timing of Active Traffic Control Devices at Rail-Highway Grade Crossings, 14-6
Countermeasures to Reduce Gate-Rushing at Crossings with Two-Quadrant Gates, 14-10

Key References

1. Coleman, F., III. & Moon, Y.J. (1996). Design of gate delay and gate interval time for four-quadrant gate system at railroad-highway grade crossings. *Transportation Research Record, 1553,* 124-131.
2. FHWA. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
3. Moon, Y. J., & Coleman, F., III. (2003). Dynamic dilemma zone based on driver behavior and car-following model at highway-rail intersections. *Transportation Research Part B: Methodological, 37*(4), 323-344.

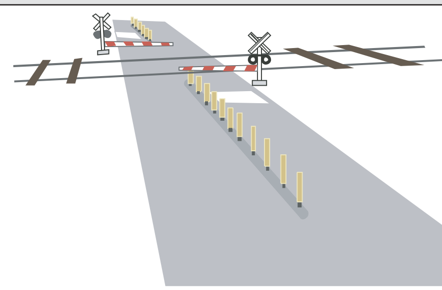
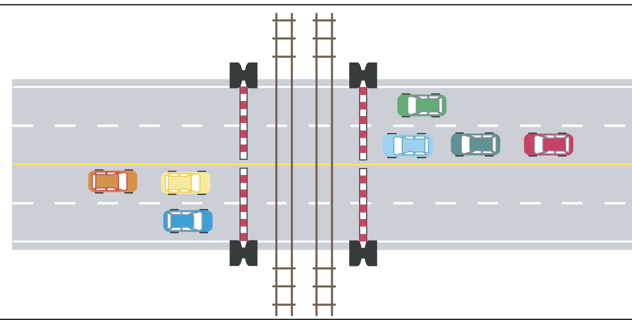
COUNTERMEASURES TO REDUCE GATE-RUSHING AT CROSSINGS WITH TWO-QUADRANT GATES

Introduction

Gate-rushing is a type of violation that occurs when drivers drive under gate arms as they are descending or around gate arms that are already in the lowered position. Although gates are some of the most restrictive crossing control devices, 9.1 crashes per 1 million trains are still occurring at crossings with two-quadrant gates (*1*). Additionally, vehicle crashes at gated crossings were significantly more likely to occur when a train struck a vehicle than when a vehicle struck a train (*1*). This is likely occurring because a driver has misjudged the speed of the train and rushed the gate(s) in an attempt to beat the train through the crossing.

Design Guidelines

Use one or more of the countermeasures below to reduce gate-rushing at rail-highway grade crossings with two-quadrant gates.

Countermeasure	Example
Install centerline barriers (flexible barriers to separate traffic (*2*))	
Install a four-quadrant gate (*3*)	

Discussion

Centerline barriers: The two unsafe behaviors that were examined with centerline barriers were gate-rushing and driver U-turns while waiting for trains to pass through the crossing. When tested at two sites, centerline barriers reduced gate-rushing by 35% on average and U-turns at gates by 82% on average (*2*). The results showed that drivers were more likely to rush the gates in clear weather and when the gate malfunctioned (i.e., activated without a train present). Drivers were also more likely to bypass the gate when more than one train was crossing with little delay between them as many drivers used the gap between successive trains to go around the gate and cross. Drivers were also more likely to make U-turns with longer gate closures, gate malfunctions, in clear weather, on weekends, and when trains stopped on the tracks. The median treatment was only tested at two crossings; however, although the frequency of unsafe behaviors varied between the crossings (likely due to site-specific characteristics), drivers' responses to the barrier countermeasure were similar in magnitude between the two different crossings.

Four-quadrant gates: Four-quadrant gates reduce gate-rushing by physically restricting drivers from driving around lowered gate arms. In a before-and-after study performed with a transition from two-quadrant to four-quadrant gates with skirts, the average number of drivers per train arrival who drove around the gate arms dropped from 2.6 to 0.0 (*3*). Driver approach speed was found to be about 10 mi/h faster with the installation of four-quadrant gates. This was likely due, however, to drivers not having to slow to follow a queue of vehicles that were bypassing the lowered gate arms. The authors recommend that four-quadrant gates be considered for crossings with one or more of the following characteristics: (1) crossings on four-lane undivided roads, (2) multitrack crossings at which the distance between tracks is greater than the vehicle length, (3) crossings without train predictors that have long and variable warning times, (4) crossings that are frequently crossed by trucks carrying hazardous materials, school buses, or high-speed passenger trains, and (5) crossings with consistent gate-rushing or crashes.

Design Issues

Engineering changes: There are engineering changes that can be made to reduce gate-rushing without the installation of additional physical roadway countermeasures. Constant warning time train predictors have been shown to reduce violations of flashing light signals and reduce the occurrence of very short clearance times at crossings with flashing lights only (*4*). Also, decreased warning times have been shown to reduce violations in general (*5*). For exact guidance, see the guideline on Timing of Active Traffic Control Devices at Rail-Highway Grade Crossings. These constant and decreased warning times improve the credibility of warning devices, thereby increasing driver trust in the system and compliance with warning devices.

Wayside horns: In a study at three crossings in a residential suburb, Raub and Lucke (*6*) found that after the transition from train horns to automated wayside horns, gate violations decreased by 68%. Additionally, residential sound levels decreased by over 10 dB in most locations within the vicinity of the crossings. Although these are both great advantages for the wayside horn systems, the horns can have false activations (i.e., activated when a commuter train stopped at a station within the warning zone) and are often sounded for longer periods of time than train horns (from the time that the gate activates to the train arrival). There is the possibility that the horns may startle drivers as evidenced by 12 drivers that stopped on the tracks. Overall, the main purpose of this countermeasure is not to reduce gate-rushing, but rather to replace locomotive horns with an auditory notification that pollutes surrounding areas to a lesser degree.

Cross References

Task Analysis of Rail-Highway Grade Crossings, 14-2
Timing of Active Traffic Control Devices at Rail-Highway Grade Crossings, 14-6
Four-Quadrant Gate Timing at Rail-Highway Grade Crossings, 14-8

Key References

1. Raub, R.A. (2009). Examination of highway-rail grade crossing collisions nationally from 1998 to 2007. *Transportation Research Record, 2122,* 63-71.
2. Khattak, A.J., & McKnight, G. A. (2008). Gate rushing at highway-railroad grade crossings: Drivers' response to centerline barrier. *Transportation Research Record, 2056,* 104-109.
3. Heathington, K.W., Fambro, D.B., & Richards, S.H. (1989). Field evaluation of a four-quadrant gate system for use at railroad-highway grade crossings. *Transportation Research Record, 1244,* 39-51.
4. Richards, S.H., Heathington, K.W., & Fambro, D.B. (1990). Evaluation of constant warning times using train predictors at a grade crossing with flashing light signals. *Transportation Research Record, 1254,* 60-71.
5. Richards, S.H. & Heathington, K.W. (1990). Assessment of warning time needs at railroad-highway grade crossings with active traffic control. *Transportation Research Record, 1254,* 78-84.
6. Raub, R.A., & Lucke, R.E. (2004). Use of automated wayside horns for improving highway-rail grade crossing safety. *ITE 2004 Annual Meeting and Exhibit.*

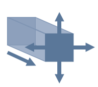
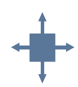
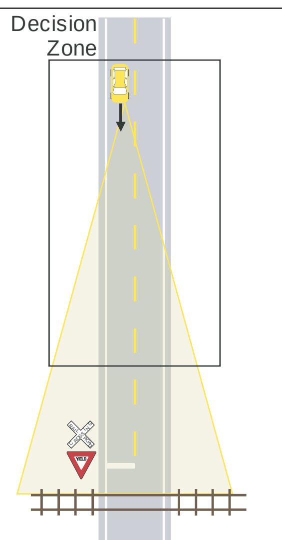
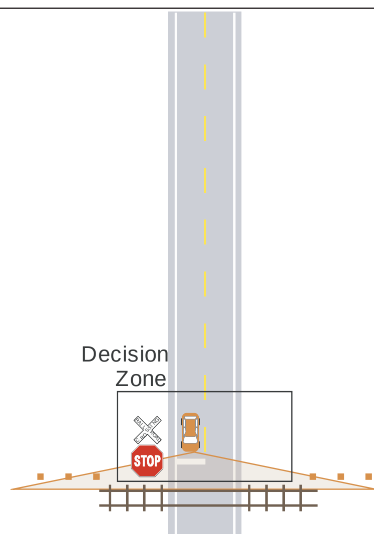
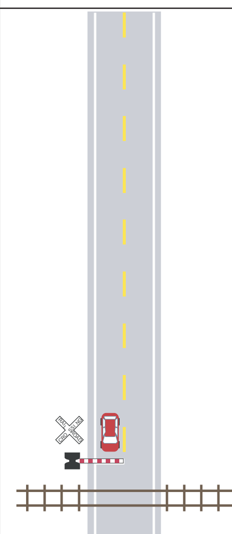
HUMAN FACTORS CONSIDERATIONS IN TRAFFIC CONTROL DEVICE SELECTION AT RAIL-HIGHWAY GRADE CROSSINGS

Introduction

This guideline refers to the human factors that apply to three different levels of control at rail-highway grade crossings: Yield signs, Stop signs, and automatic gates. The MUTCD (*1*) states that a Yield or Stop sign should be part of the crossbuck assembly. The Yield sign is the default choice, however Stop signs are currently the more prevalent traffic control device used at grade crossings (*2*). Interest in the use of Yield signs at passive crossings is increasing. Also, under certain conditions, the use of active control devices may be the most suitable solution. The following factors can be used when determining the appropriate level of control.

Design Guidelines

The table below outlines the human factors issues to consider when installing a Yield sign, Stop sign, or active control device.

Driver Factor	Yield Sign	Stop Sign	Active Control
Sight lines	• Provide a large sight triangle	• Provide at minimum a sight triangle along the track	• Few requirements for sight lines
Decision factors	• Low – driver needs information to make a gap acceptance decision	• Medium – driver needs information to make a go/no-go decision	• High – driver needs little additional information
Timing elements	• Provide enough time to decide to stop or continue while moving	• Provide clearance time for large vehicles that are stopped at the crossing	• Provide appropriate light timing to allow vehicles to stop or cross after flashing lights activate
Workload	• High	• Medium	• Low
Train speed perception	• Visual expansion and translational cues are provided 	• Provide speed perception cues along the track – only visual expansion cues provided 	• Not necessary for decision
Decision zones (Graphics not to scale) Direction of traffic flow 	 (Width of sight triangle only limited by roadside objects.)		

Discussion

Compliance issues are not addressed in this discussion since they are covered in "Task Analysis of Rail-Highway Grade Crossings" on page 14-2 as well as the design issues section below. Exact guidance regarding when to install each control device can be found in the Highway/Rail Grade Crossing Technical Working Group document (*3*) and the MUTCD (*1*).

Yield sign: The Yield sign provides the lowest level of control discussed in this guideline. The MUTCD standard states that a Yield sign should be the minimum additional level of control at passive grade crossings with crossbucks. The amount of information provided by a Yield sign is minimal since the location of the train (if present) and the appropriate driver action are not provided. As drivers are approaching the crossing, the decision they need to make is similar to a gap acceptance decision; they need to judge the gap between their vehicle and the train (if present) to determine if yielding is required. To make this judgment, a large clear zone is necessary in the approach area to enable drivers to see the train from a distance that allows them to stop or proceed. However, this means that drivers will have better speed perception cues than they do at Stop signs, since they observe the train from a greater distance from the crossing. They receive not only the visual expansion cues, but also translational cues from the trains' forward motion. Because a stop is not required at Yield signs, all of the decision making occurs farther before the crossing than it does for the Stop sign. Additionally, drivers have greater latitude in their decision making than they do at crossings with a greater level of control. This puts a demand on drivers to judge their speed relative to a moving train and decide the safe action.

Stop sign: The Stop sign provides an intermediate level of control between the Yield sign and active gates. The sign requires drivers to stop and then to make a go/no-go decision based upon the presence of a train. Since drivers are making the go/no-go decision while stopped at the tracks (at a later point than they do for the Yield sign), the demands for sight lines are less significant and occur along the track. However, while looking almost straight down the tracks, drivers have poor speed perception of the oncoming train. Additionally, from the stopped position, larger vehicles take longer to accelerate over the tracks, which they need plenty of time to do before the train arrives. This puts a demand on the sight distance of the train to give drivers time to make a go decision and then cross the tracks.

Active Gates: Active traffic control devices with gates provide a high level of control, thus removing most of the decision-making demands from drivers. Drivers have few requirements in the way of sight lines because they know if a train is approaching by the status of the device. Train speed perception cues are not necessary since the active device warns that a train is approaching. In terms of vehicle kinematics, the timing of the gate should give drivers enough time to stop or proceed as appropriate before the gate descends. A related device is flashing lights without gates. This device also removes most of the decision-making demands from the driver but does not provide a physical barrier between the vehicle and the crossing.

Design Issues

Compliance and other internal factors can largely affect driver decision-making at traffic control devices in various ways. At Yield signs, low train expectancy and/or high familiarity with the crossing can lessen the degree of visual search performed on the approach. At Stop signs, low train expectancy and/or high familiarity can push for a "go" decision or decrease stopping occurrences. Additionally, Sanders, McGee, and Yoo (*4*) state that the driver should be able to perceive that a stop is necessary and enforcement should equal that of a Stop sign at a highway intersection. If a Stop sign is present, the driver should not be able to detect a train without stopping at the sign. For active control devices, low credibility or reliability, as discussed in "Task Analysis of Rail-Highway Grade Crossings" on page 14-2, can contribute to gate-rushing.

Cross References

Task Analysis of Rail-Highway Grade Crossings, 14-2
Timing of Active Traffic Control Devices at Rail-Highway Grade Crossings, 14-6
Four-Quadrant Gate Timing at Rail-Highway Grade Crossings, 14-8

Key References

1. FHWA. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
2. Lerner, N. D., Llaneras, R. E., McGee, H. W., & Stephens, D. E. (2002). *NCHRP Report 470: Traffic-Control Devices for Passive Railroad-Highway Grade Crossings.* Washington, DC: Transportation Research Board.
3. Highway/Rail Grade Crossing Technical Working Group (TWG) (2002). *Guidance on Traffic Control Devices at Highway-Rail Grade Crossings*. FHWA. Retrieved July 2011 from http://safety.fhwa.dot.gov/xings/collision/.
4. Sanders, J.H., McGee, H.W., & Yoo, C.S. (1978). *Safety Features of Stop Signs at Rail-Highway Grade Crossings. Volume II. Technical Report* (FHWA-RD-78- 41). Washington, DC: FHWA.

CHAPTER 15

Special Considerations for Urban Environments

METHODS TO INCREASE DRIVER YIELDING AT UNCONTROLLED CROSSWALKS

Introduction

This guideline provides an overview of some *methods that can be used to increase driver yielding at uncontrolled crosswalks*. Uncontrolled crosswalks are crosswalks that cross the roadway at a location where no stop or signal control exists. They may be midblock or at an intersection with two-way traffic control. Uncontrolled crosswalks include those which have pedestrian signals such as a half signal or HAWK signal. These crosswalks are often desirable to improve pedestrian access to points that lie between, and perhaps far from, an associated controlled intersection crossing. However, at uncontrolled locations on two-lane roads, marked crosswalks provide no crash rate reduction when compared to unmarked crosswalks (*1*). Although pedestrians in marked crosswalks are more likely to have drivers immediately yield to them, this higher rate of yielding may lead to multiple-threat collisions on roadways with multiple lanes in each direction (*2*). Therefore, it is important to ensure that pedestrians using marked crosswalks and drivers approaching marked crosswalks have adequate sight lines and actively look for one another.

Design Guidelines

Improve sight lines between the driver and the pedestrian(s) by:

- Installing yield lines
- Installing bulbouts
- Prohibiting parking between the yield line and the crosswalk

Convey the need for drivers to look for crossing pedestrians by:

- Installing Roving Eye displays
- Installing “Yield Here to Pedestrians” signs (along with yield lines)

The width of the bulbout (in feet) that may be seen from the nearest travel lane at the stopping sight distance from the yield line is show in the table below.

Posted Speed	Deceleration Level (ft/s^2)	Parking Distance from Crosswalk (in feet)					
		0	***10***	***20***	***30***	***40***	***50***
30 mi/h	*11.2*	0.2	0.7	1.3	1.8	2.4	3.0
	13.8	0.2	0.8	1.4	2.1	2.7	3.3
	17.7	0.2	0.9	1.6	2.3	3.0	3.7
40 mi/h	*11.2*	0.1	0.5	0.8	1.2	1.5	1.9
	13.8	0.1	0.5	0.9	1.3	1.7	2.1
	17.7	0.1	0.6	1.1	1.5	2.0	2.4

Assumptions: Driver eye is at the midpoint of the left half of the vehicle; the roadway is straight; the pedestrian stands in the middle of the bulbout (when looked at along the axis of the roadway); perception-response time is 1.6 s; vehicles are parked 1 ft from the curb; deceleration levels are from AASHTO (*3*) “comfortable” level (3.4 m/s^2); vehicles in the parking lane are parked up to the yield line but not between the yield line and the crosswalk.

Discussion

Improve sight lines: The desired driver action at an uncontrolled crosswalk varies based upon the presence or absence of a pedestrian. In a field study of midblock crosswalks, the addition of yield lines and “Yield to Pedestrians” signs increased the likelihood that drivers look to the right for crossing pedestrians (*4*). For drivers who yielded, the treatments also led to an increase in distance between the vehicle and the crossing pedestrian. However, the proportion of drivers who yielded only increased with the addition of the treatments when the sight distance was adequate to see waiting pedestrians. Without improvements in sight distance, drivers with advance yield markings are unable to see pedestrians in their peripheral vision due to cars parked in the parking lane. Garay-Vega, Fisher, and Knodler (*4*) suggest that this situation is comparable to that which causes multiple-threat collisions. These collisions occur when the pedestrian enters traffic in front of a stopped vehicle and collides with another vehicle traveling in the same direction in a lane past the stopped vehicle.

Convey need to look for pedestrians: The pushbutton-activated roving eye treatments (animated eye graphics included in signals) were tested at two sites with medians, crosswalks, and yield bars (*5*). Although only 30% to 40% of pedestrians activated the roving eyes, activation significantly increased at one site with enforcement. The roving eyes generally improved yielding behavior in both directions, though low levels of pedestrian activation impaired the results.

Design Issues

The issue of whether to mark the crosswalk is controversial. Zegeer (*1*) found that multiple-threat collisions are much more likely to occur at marked crosswalks. However, in a study of marked and unmarked matched pairs of crosswalks, Ragland and Mitman (*2*) found that pedestrians in marked crosswalks were more likely to have drivers immediately yield to them. Although when asked, significantly fewer drivers than pedestrians knew that pedestrians legally have the right of way at marked midblock crosswalks (44% to 74%, respectively). It is hypothesized that pedestrians exhibit an ordinary level of caution in marked crosswalks because they know drivers must yield to them and/or their experience has taught them that more drivers are likely to yield. However, in unmarked midblock crosswalks, 72% of drivers and 76% of pedestrians knew that pedestrians did not have the right of way. It would be reasonable to assume that pedestrians would exhibit greater caution in crossing under these conditions either because they know that they do not have the right-of-way and/or because their experience has been that drivers will not yield. Indeed, in the unmarked crosswalks, pedestrians waited for larger gaps (5/6 sites) and moved at a faster pace (4/6 sites) than in the marked crosswalks.

Even with the installation of bulbouts and the recommended parking restrictions, pedestrians may not be able to be seen by drivers depending on the part of the bulbout on which they stand. Fitzpatrick et al. (*6*) list the body depth for standing area calculations as approximately 1.6 ft. The table on the previous page shows the width of the bulbout (perpendicular to the traveled way) that can be seen by drivers passing in the nearest lane. Though the MUTCD (*7*) guidance recommends that yield or stop lines be installed 20 to 50 ft in advance of the nearest crosswalk line, the inclusion of the 0-ft and 10-ft parking distances simulate multiple-threat crash scenarios where vehicles may stop right next to the crossing pedestrian. The widths would decrease if vehicles wider than 7 ft parked near the curb. Pedestrians may not feel comfortable standing right on the edge of the bulbout, especially those using wheelchairs or other assistive devices.

Cross References

Human Factors Considerations in Traffic Control Device Selection at Rail-Highway Grade Crossings, 14-12
Methods to Increase Compliance at Uncontrolled Crosswalks, 15-4
Methods to Reduce Driver Speeds in School Zones, 15-6

Key References

1. Zegeer, C.V., Stewart, J.R., Huang, H.H., Lagerwey, P.A., Feaganes, J., and Campbell, B.J. (2005). *Safety Effects of Marked versus Unmarked Crosswalks at Uncontrolled Locations: Final Report and Recommended Guidelines.* (FHWA-HRT-04-100). McLean, VA: FHWA.
2. Ragland, D.R. & Mitman, M.F. (2008). *Driver/Pedestrian Understanding and Behavior at Marked and Unmarked Crosswalks* (UCB-ITS-TSC-2008-10). Berkeley: University of California Traffic Safety Center.
3. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.
4. Garay-Vega, L., Fisher, D.L., & Knodler, M.A. (2008). Drivers' performance in response to sight-limited crash scenarios at midblock crosswalks: Evaluation of advance yield markings and symbolic signage. *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting,* 1835-1839.
5. Nee, J., & Hallenbeck, M.E. (2003). *A Motorist and Pedestrian Behavioral Analysis Relating to Pedestrian Safety Improvements.* (WA-RD 560.1). Olympia: Washington State Department of Transportation.
6. Fitzpatrick, K., Turner, S.M., Brewer, M., Carlson, P.J., Ullman, B., Trout, N.D., & et al. (2006). *TCRP Report 112/NCHRP Report 562: Improving Pedestrian Safety at Unsignalized Crossings.*Washington, DC: Transportation Research Board.
7. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.

METHODS TO INCREASE COMPLIANCE AT UNCONTROLLED CROSSWALKS

Introduction

Methods to increase compliance at uncontrolled crosswalks refers to treatments that improve pedestrian safety. These improvements are realized through safer pedestrian behavior and increased compliance with crossing treatments. These treatments should increase safety without decreasing crosswalk use and without excessive pedestrian delay. It is also important that they are designed so that pedestrians will find the treatments to be beneficial and thus activate them as necessary. The following guideline describes the information needs of drivers at uncontrolled crosswalks. These needs should be provided for by using the appropriate engineering countermeasures, roadway design treatments, and traffic control devices. Note that not all of the potential treatments suggested below are warranted on all road types based on vehicular and pedestrian traffic volumes.

Design Guidelines

- Install a median refuge island to influence location choices for pedestrian crossings.
- Provide a maximum pedestrian delay of 30-60 s when using signalized treatments.
- Clearly indicate the required driver actions.

COMPLIANCE WITH VARIOUS TREATMENTS AT UNCONTROLLED CROSSWALKS

Treatment Type	Average Driver Yielding Compliance	Pedestrian Crosswalk Use	Pedestrian Activation	Average Initial Pedestrian Delay (s)*
HAWK Signal Beacon	99%	90%	70%	9.63
Half Signal	98%	80%	67%	17.06
Midblock Signal	95%	95%	67%	26.35
In-Street Signs	90%	93%	N/A	2.15
Pedestrian Crossing Flags	74%	88%	17%	2.72
Overhead Flashing Beacons (Automated Pedestrian Detection)	67%	87%	58%***	5.62
Overhead Flashing Beacons (Pushbutton Activation)	49%	82%	28%	5.44
Median Refuge	29%	82%	N/A	9.22
High-Visibility Signs/Markings	20-91%**	89%	N/A	2.39

*Combined delay at start of crosswalk and in median.
**Average compliance lower on 35 mi/h roadways than 25 mi/h roadways.
***Reasons the system did not activate include: detector malfunctions, missed detections, and crosswalk incompliance.
Source: Fitzpatrick et al. (*1*)

EXAMPLE TREATMENTS

HAWK Signal Beacon

Median Refuge Island

In-Street Signs

Source: Fitzpatrick et al. (*1*)

Discussion

Median refuge islands: When median refuges were installed, significant numbers of pedestrians used them for crossing (36-46%, *2*). These percentages increased even more with the addition of crosswalks and yield bars. Providing a pedestrian refuge decreases nearside gap rejection (*3*) and allows pedestrians to cross the roadway in two stages.

Another type of median is the extended median, sometimes used at split midblock signals. With this type of median, delay to vehicles is reduced by requiring the pedestrian to activate the signal for one half of the street, cross to the median, walk 100 ft down the center median, and push another button to activate the signal on the other half of the street. In an on-street survey, Ullman, Fitzpatrick, and Trout (*4*) found that pedestrian opinions of extended medians varied based upon the pedestrian's abilities. At the location with a greater number of disabled and older pedestrians, the extended median was viewed more favorably than at the location without this pedestrian population, where it was seen as an unnecessary delay.

Pedestrian signal response time: Van Houten, Ellis, and Kim (*5*) studied two signalized midblock crosswalks in Miami, Florida, by varying the minimum green time of the oncoming vehicles to 30, 60, and 120 s. It was found that the percentage of pedestrians who violated the "Don't Walk" signal was greater at both intersections when the 60- or 120-s minimum green times were used. Proportionately more pedestrians violated the signal at 120 s than at 60 s. As the length of the minimum green time increased, more pedestrians were trapped in the crosswalk (23% at 120 s). When the minimum green time was short, most pedestrians waited for the "Walk" sign, decreasing their likelihood of becoming trapped. However, when the minimum green time was 30 s, vehicle delay was longer than the pedestrian delay. Additionally, increasing the pedestrian clearance time to allow slower pedestrians to cross may cause longer minimum green times and thus increase pedestrian violations. FHWA (*6*) recommends an almost immediate response to pedestrian activation to encourage compliance.

Using on-street pedestrian surveys, Ullman et al. (*4*) found that about 75% of participants at six sites stated that they should have to wait less than a minute before being able to cross the street. However, this value may differ when examined as actual pedestrian actions. A short response time to pedestrian button pushing is important because if pedestrians push the button and do not get a fast response, they may cross at the first ample gap (depending on traffic levels). Then, when the signal turns red for drivers, no pedestrians will be crossing, possibly encouraging driver disrespect for the signal in the future (*6*).

Provide a clear indication of the required driver action: The red signals and beacons form a class of warning devices that clearly signifies the required driver action. Fitzpatrick et al. (*1*) found that red signal treatments had compliance rates above 94%. The treatments that showed a red indication had a statistically higher compliance rate than those that did not. It was hypothesized that this is because they send a clear message to "Stop." Nearly all of these devices were tested on busy, high-speed arterials (*1*).

Design Issues

Fluorescent yellow-green is presented in the MUTCD (*7*) as a color option for some pedestrian crossing signs; however, Clark, Hummer, and Dutt (*8*) found that the use of the color only increased slowing or stopping behavior at three of seven sites studied and did not change conflict rates significantly.

A potential issue is pedestrians congregating on the sidewalk near midblock crosswalks. If uncontrolled crosswalks are installed near locations where groups of pedestrians stand to socialize or wait for the bus, it may be more difficult for passing drivers to notice a pedestrian who is waiting to cross against the background of all of the stationary pedestrians.

Cross References

Countermeasures for Improving Accessibility for Vision-Impaired Pedestrians at Roundabouts, 10-10
Methods to Increase Driver Yielding at Uncontrolled Crosswalks, 15-2

Key References

1. Fitzpatrick, K., Turner, S.M., Brewer, M., Carlson, P.J., Ullman, B., Trout, N.D., & et al. (2006). *TCRP Report 112/NCHRP Report 562: Improving Pedestrian Safety at Unsignalized Crossings.* Washington, DC: Transportation Research Board.
2. Nee, J., & Hallenbeck, M.E. (2003). *A Motorist and Pedestrian Behavioral Analysis Relating to Pedestrian Safety Improvements.* (WA-RD 560.1). Olympia: Washington State Department of Transportation.
3. Hunt, J., & Abduljabbar, J. (1993). Crossing the road: A method of assessing pedestrian crossing difficulty. *Traffic Engineering and Control, 34*(11), 526-532.
4. Ullman, B., Fitzpatrick, K., & Trout, N. (2004). On-street pedestrian surveys of pedestrian crossing treatments. *Proceedings of the ITE 2004 Annual Meeting and Exhibit.*
5. Van Houten, R., Ellis, R. D., & Kim, J.-L. (2007). Effects of various minimum green times on percentage of pedestrians waiting for midblock "walk" signal. *Transportation Research Record, 2002,* 78-83.
6. FHWA (2006). Federal Highway Administration University Course on Bicycle and Pedestrian Transportation. Lesson 12: Midblock Crossings. Retrieved July 2011 from http://www.fhwa.dot.gov/publications/research/safety/pedbike/05085/pdf/lesson12lo.pdf.
7. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
8. Clark, K. L., Hummer, J.E., & Dutt, N. (1996). Field evaluation of fluorescent strong yellow-green pedestrian warning signs. *Transportation Research Record, 1538,* 39-46.

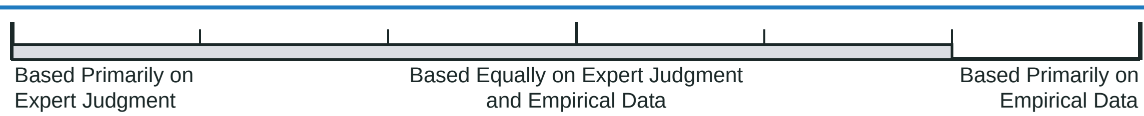
METHODS TO REDUCE DRIVER SPEEDS IN SCHOOL ZONES

Introduction

Methods to reduce driver speeds in school zones refers to traffic control devices and pavement markings that are used to encourage drivers to drive at lower speeds in school zones. Maintaining safe speeds is particularly important in school zones for multiple reasons: (1) children have a greater tendency to behave unexpectedly near roadways than adults (*1*), (2) the probability of a pedestrian fatality rises from about 10% to approximately 60% when vehicle-impact speeds increase from 23 to 28 mi/h (*2*), (3) providing a reduced speed zone gives drivers a reduced stopping distance when forced to attempt to stop in reaction to a child hazard, and (4) reduced driver speeds also provide safer gaps for children to cross the street (*3*). Application of the guidelines below should encourage slower driving and facilitate the safety of children in school zones.

Design Guidelines

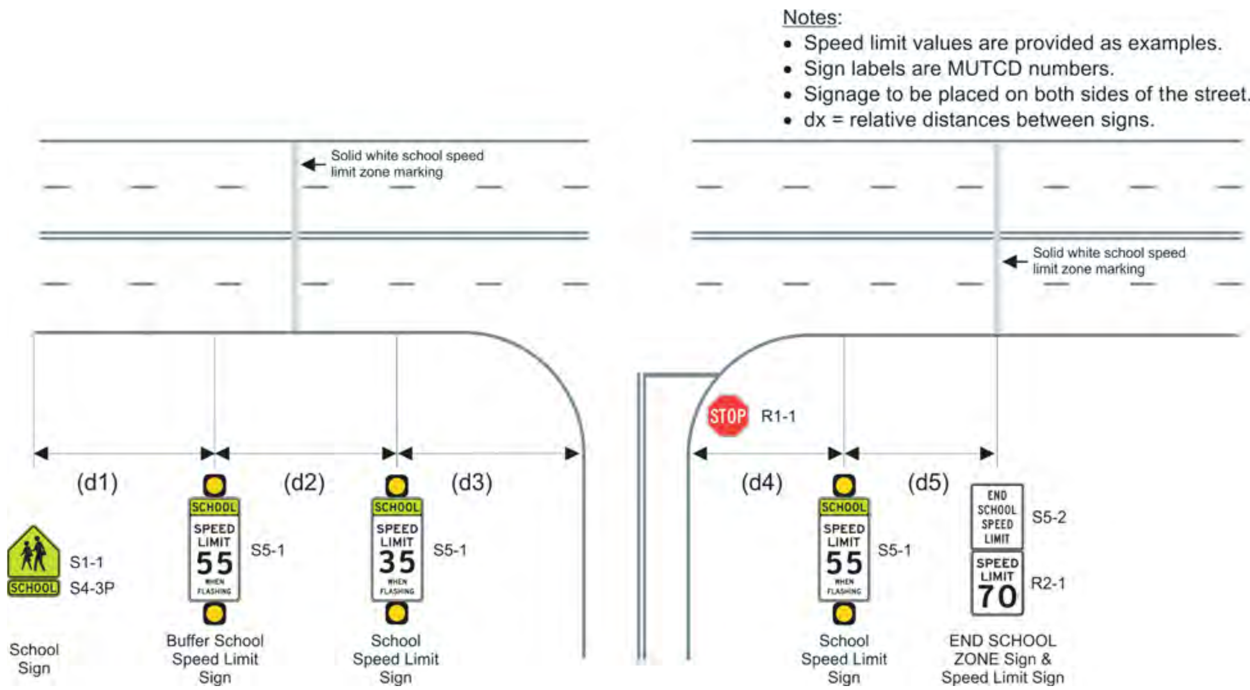
<table>
<tr><th>School Zone Speed Characteristic</th><th colspan="2">Guideline</th></tr>
<tr><td>Active Times (4)</td><td colspan="2">The school zone speeds indicated on the signs should be in effect only from:
• 30 min before to 5 min after classes begin
• The beginning to the end of lunch periods for open campuses
• 5 min before to 30 min after classes end</td></tr>
<tr><td rowspan="4">School Speed Limit Value (4)</td><td>85th Percentile Speed</td><td>Suggested School Zone Speed Limit</td></tr>
<tr><td>< 55 mi/h</td><td>Not more than 15 mi/h below the 85th percentile speed or posted speed. Not to exceed a 35-mi/h school speed limit.</td></tr>
<tr><td>55 mi/h</td><td>20 mi/h below the 85th percentile speed or posted speed.</td></tr>
<tr><td>> 55 mi/h</td><td>Use a buffer zone to transition to a 35-mi/h school speed limit.</td></tr>
<tr><td>School Speed Limit Zone Length (4)</td><td colspan="2">• As short as 400 ft in urban areas with speeds ≤ 30 mi/h
• 1000 ft in rural areas with posted speeds ≥ 55 mi/h</td></tr>
<tr><td>School Buffer Zone (4)</td><td colspan="2">• Use when the difference between the regulatory speed limit and the school speed limit is > 20 mi/h
• Typically 500 ft in length
• Buffer zone beacons can activate up to 5 min before school speed zone beacons (see figure on next page)</td></tr>
<tr><td>School Entrance Warning Assembly (4)</td><td colspan="2">Do not use if:
• A school speed limit zone is present
Conditions for use could include:
• Crash records show a need to advise drivers to reduce speeds
• The majority of students are transported by bus or private vehicle
• No provisions are made for students to walk to/from school
• No left- or right-turn lanes are present on the highway at the school driveway, or queue spillover from turning vehicles is present, or methods to address the spillover have not worked
• The entrance is not controlled by traffic signals</td></tr>
<tr><td>Sign/Device Choice (2)</td><td colspan="2">The signs indicating a school speed limit were effective when the lights were flashing, and caused the greatest speed reductions on 35-mi/h roadways.</td></tr>
<tr><td>Speed Monitoring Displays (5)</td><td colspan="2">Speed monitoring displays were effective in reducing vehicle speeds by 17.5% and 12.4% in the short- and long-term studies, respectively.</td></tr>
</table>



Discussion

A key data source in this area and a key contributor to this guideline is Fitzpatrick, Brewer, Obeng-Boampong, Park, and Trout (*4*), in which a variety of methods were used to document existing knowledge and develop guidelines for school zone traffic control devices. Key methods included a literature review, a survey of practitioners on signing and marking practices, a telephone survey of law enforcement officers, and a review of state and local guidelines for school zones. The figure below (adapted from *4*) shows key results for school zone speed limits.

SCHOOL ZONE SPEED LIMITS



Source: Fitzpatrick et al. (*4*)

Design Issues

The effectiveness of school zone flashers on vehicular speed is unclear. Aggarwal and Mortensen (*6*) found a significant reduction in vehicle speeds with the use of advance school flashers. When Hawkins (*7*) tested the beacons on school zones on highways, however, the speed differences were limited. One benefit mentioned by Hawkins (*7*) and observed by Hawkins (*8*) on speed limit signs is that flashers also serve the purpose of indicating when the school zone is active.

Cross References

Speed Perception, Speed Choice, and Speed Control Guidelines, 17-1
Methods to Increase Driver Yielding at Uncontrolled Crosswalks, 15-2
Task Analysis of Rail-Highway Grade Crossings, 14-2

Key References

1. Tay, R., & Li, S.J. (2008). Drivers' perceptions and reactions to chain link fence. *Transportation Research Board 87th Annual Meeting Compendium of Papers* [CD ROM].
2. Saibel, C., Salzberg, P., Doane, R., & Moffat, J. (1999). Vehicle speeds in school zones. *ITE Journal, 69*(11), 38-42.
3. Saito, M., & Ash, K.G. (2005). *Evaluation of Four Recent Traffic Safety Initiatives, Volume IV: Increasing Speed Limit Compliance in Reduced Speed School Zones.* (Report UT-05.13). Salt Lake City: Utah Department of Transportation.
4. Fitzpatrick, K., Brewer, M.A., Obeng-Boampong, K., Park, E.S., & Trout, N.D. (2009). *Speeds in School Zones.* (FHWA/TX-09/0-5470-1). College Station: Texas Transportation Institute.
5. Lee, C., Lee, S., Choi, B., & Oh, Y. (2006). Effectiveness of speed-monitoring displays in speed reduction in school zones. *Transportation Research Record, 1973*, 27-35.
6. Aggarwal, G.C., & Mortensen, S.L. (1993). Do advance school flashers reduce speed? *ITE Journal, 63*(10), 24-30.
7. Hawkins, N.R. (1993). Modified signs, flashing beacons and school zone speeds. *ITE Journal, 63*(6), 41-44.
8. Hawkins, H.G. (2007). Rear-facing school speed limit beacons. *ITE Journal, 77*(6), 18-23.

SIGNAGE AND MARKINGS FOR HIGH OCCUPANCY VEHICLE (HOV) LANES

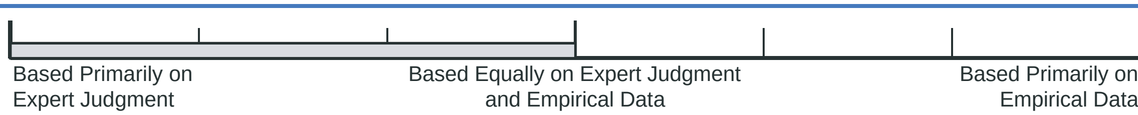
Introduction

Managed and reserved lanes are lanes usually designed for roadway networks in highly congested metropolitan regions where High Occupancy Vehicles (HOV) are promoted and maintained as part of a network freeway management program. "An exclusive HOV roadway is an entire highway facility reserved at all times solely for the use of buses or buses and other HOVs. This facility offers buses and HOVs a high level of service and decreases travel time for the users" (*1*). Other HOV roadways are only exclusive during certain hours of the day. These lanes have various restrictions that do not apply to the normal travel lanes. The signage and markings used to discriminate these lanes is essential for motorists to understand usage rules and the special nature of the lane.

Design Guidelines

The following recommendations should be considered when designing signage and markings of HOV lanes. These recommendations should facilitate motorists' understanding of usage rules and the special nature of these lanes.

Design Element	Design Guideline
Signage	• Use "HOV" text rather than HOV diamond symbol on signage (*2*) • Avoid using "HOV/TOLL Lane" banner (*2*) • Provide distance destination signs and interchange sequence signs in advance of all access points to and from managed lanes (*2*). • Preferential lane sign information sequence (M1): – Top line: lanes to which the preferential treatment applies (e.g., left lane) – Middle line: applicable vehicles (e.g., buses only) – Bottom line: applicable time and date (e.g., 7-9 am, Monday-Friday) • If sign is mounted overhead, then time and date should be separated by a downward arrow • Use overhead-mounted signs instead of shoulder-mounted signs where possible (*3*) • Lane control signals (e.g., red X indication in closed lanes) are well understood and can be used (*3*).
Markings	• Avoid using the word "only" and the arrow symbol (*4*) • Avoid using "No Exit" text on the roadway (*4*) • Contra-flow lanes: use yellow pavement markings to delineate between HOV and mixed-use lanes • Concurrent flow lanes: use white pavement markings to delineate, and solid lines to show areas where crossing is not allowed • Use solid HOV diamond symbols instead of outlines (*3*).



Discussion

There are relatively few data sources that can be used to develop comprehensive guidelines on this topic. The studies by Chrysler (*2*, *4*) provide the best-available data for the design of signs and markings, and the guidelines above rely quite heavily on these laboratory studies. In Chrysler (*2*), computer-based surveys were used to obtain data from 142 drivers in Texas. The surveys used video animations and still images of signs to assess driver comprehension of managed lane signs that presented information related to pricing, occupancy, and destinations. Although there were some methodological concerns about the legibility of the animations used, the study yielded useful information on the characteristics of managed lane signs that seem to be associated with the highest levels of comprehension. For example, Chrysler found that letters “HOV” were better understood vs. the diamond symbol. Drivers also showed poor comprehension with the “HOV/TOLL Lane” banner. Half of the respondents incorrectly understood the banner to mean that only carpools are allowed, and they must pay a toll. This misunderstanding would prevent toll-paying single occupant vehicle drivers from entering the lane when they were actually allowed. Also, the HOV diamond symbol in the corner of the sign is still misunderstood by 15-25% of drivers to mean “Official Vehicles Only.” The text “HOV” was well understood by over 90% of participants (*2*).

Advanced destination signing is an important determinant of whether drivers will use a managed lane. Previous studies show that one of the main reasons drivers do not enter HOV lanes is uncertainty about destinations served. Chrysler found that distance destination signs and interchange sequence signs should be provided in advance of all access points to and from managed lanes. Interchange sequence signs for managed lane exits may need to be made more distinct to avoid confusion with signing for the general purpose lanes (*2*).

Design Issues

A key topic in the design of managed lanes is whether the lane(s) will offer limited access or continuous access. In Jang and Chan (*5*), an in-depth statistical evaluation of differential safety performance exhibited by these two types of HOV facilities was conducted. When compared with HOV lanes in continuous-access facilities, HOV lanes in limited-access facilities experienced a higher percentage of collisions compared with other lanes, a higher number of total collisions per mile per hour, and a higher number of severe collisions per mile per hour; also, the collision rates measured by traffic volume (per million vehicles travelled) offer the same differential in performance. The differential for left lanes was somewhat different from the pattern for HOV lanes. Compared with left lanes in continuous access facilities, left lanes in limited-access facilities had a higher percentage of collisions and a higher overall collision rate, but a lower rate of severe collisions (*5*).

Cross References

Interchanges Guidelines, 12-1
Signing Guidelines, 18-1

Key References

1. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
2. Chrysler, S.T., & Nelson, A.A. (2009). *Driver Comprehension of Managed Lane Signing*. (FHWA/TX-09/0-5446-3). College Station: Texas Transportation Institute.
3. McGhee, C.C. (1998). *Traffic Control for High Occupancy Vehicle Facilities in Virginia*. (VTRC 98-R25). Charlottesville: Virginia Transportation Research Council.
4. Chrysler, S.T., Williams, A.A., & Fitzpatrick, K. (2008). *Driver Comprehension of Signing and Markings for Toll Facilities*. (FHWA/TX-08/0-5446-2). College Station: Texas Transportation Institute.
5. Jang, K., & Chan, C.-Y. (2009). High-occupancy-vehicle lane configurations and safety performance of California freeways: Investigation of differential distributions and statistical analysis. *Transportation Research Board 88th Annual Meeting Compendium of Papers* [CD-ROM].

SIGHT DISTANCE CONSIDERATIONS FOR URBAN BUS STOP LOCATIONS

Introduction

Sight distance considerations for urban bus stop locations refers to sight line issues that stem from the placement of urban bus stops. Bus stop placement and design are dependent on a multitude of factors including vehicle delays, bus delays, pedestrian waiting areas, cost, safety, and others. Two percent of all pedestrian collisions in urban areas occur at bus stops (*1*), primarily because the bus obstructs the view of oncoming vehicles and the pedestrians who cross in front of the bus. This guideline discusses the issues related to sight distance and visibility at bus stops.

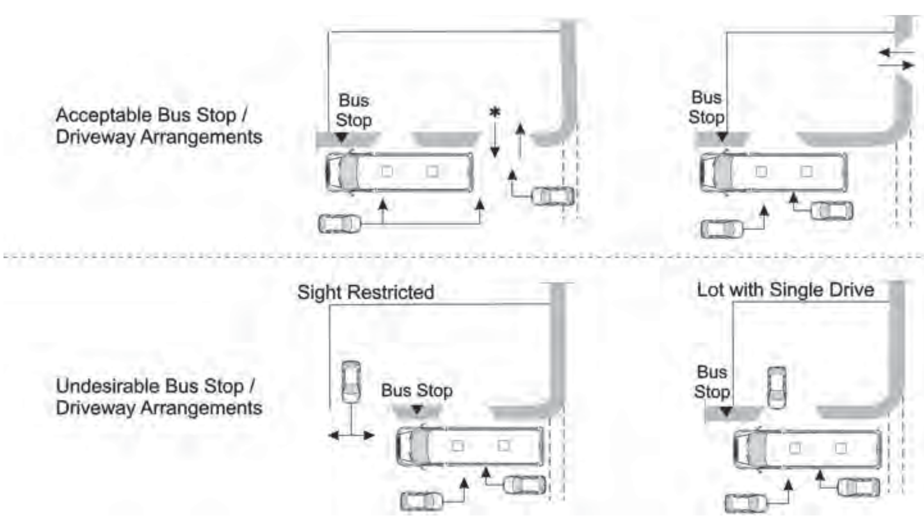
Design Guidelines

The following guidelines describe issues related to sight distance and driver crash risks for far-side, near-side, and midblock bus stop locations. These issues can be used to identify potential pitfalls when designing bus stops at specific locations (*2*).

Bus Stop Location	Sight Distance Issues	Driver Crash Risks
Far-side Stop	May block sight distance for: • Crossing vehicles • Crossing pedestrians	May increase rear-end crashes as drivers don't expect buses to stop on the far-side after stopping at a red light.
Near-side Stop	May block sight distance for: • Crossing vehicles stopped to the right of the bus • Crossing pedestrians • Curbside traffic control devices	Increased conflicts with vehicles turning right.
Midblock Stop	None	Encourages pedestrians to cross midblock.

- Bus stops should be located to provide maximum sight distance to all critical roadway elements (*1*)
- Bus stops should not be placed near driveways, on curves or superelevated locations, or on steep grades (*1*,*3*).
- Bus stops should not be obscured by trees, poles, buildings, signs, etc. (*3*, *4*)
- Adequate lighting should be provided at bus stops (*3*)
- Near-side bus bays should be avoided because they are likely to obstruct sight distance to traffic control devices and pedestrians (*2*)

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data



While visibility is enhanced for many of the movements, sight restrictions are still present for left turning vehicles.

Source: recreated from Texas Transportation Institute, Texas A&M Research Foundation and Texas A&M University (*2*)

Discussion

One of the factors that results in bus collisions with vehicles or pedestrians is the lack of adequate sight distance or sight lines. A review of pedestrian safety research (*1*) concluded that 2% of pedestrian collisions in urban areas occurred at bus stops. Most of these collisions did not occur between a pedestrian and a bus; rather, the bus created a visual barrier between the approaching vehicles and the pedestrians who crossed in front of the bus. In addition, visual obstructions outside of the bus, such as signs, shrubbery, wide columns, and other obstacles may block the bus operators' view of pedestrians (*4*). Bus stops that are poorly located relative to the roadway edge can lead to poor visibility of pedestrians. A bus stop that is set back too far from the curb for the operator to see pedestrians may lead pedestrians to encroach into the roadway in an attempt to be more visible. Finally, a lack of lighting can reduce the visibility of pedestrians both at bus stops and while crossing the street to approach or leave the bus stop.

Many factors affect the decision whether to place a bus stop at the near or far side of an intersection, or at midblock. Several studies (e.g., *5*, *6*) suggest that far-side bus stops can enhance pedestrian safety by eliminating sight distance restrictions associated with the stopped bus, primarily because they make pedestrians more visible to motorists approaching from behind the bus—with these bus stops, pedestrians are encouraged to cross the street behind the bus rather than in front of the bus. Also, far-side stops are less likely to obscure motorists' view of traffic signals, signs, and pedestrians, and they reduce conflicts between buses and right-turning vehicles (*3*). However, the number of rear-end crashes may increase because drivers don't expect buses to stop on the far side after stopping at a red light.

Near-side stop locations require alighting passengers to cross the street in front of the bus, which can obscure the sight lines from surrounding vehicles to the pedestrians. Also, the buses can block right-turning motorists' sight lines to pedestrians or slow-moving vehicles in the cross street. However, near-side stops can be effective where there are not heavy volumes of right-turning vehicles at the intersection. The guidelines in Texas Transportation Institute et al. (*2*) recommend that bus bays should be avoided for near-side bus stops because they are likely to obstruct sight distance to traffic control devices and pedestrians.

The guidance in Metcalf and Bond (*3*) suggests that, although there are generally no sight distance issues with midblock bus stops, these locations should be used when the use of near-side and far-side stop locations are not feasible due to safety considerations at the intersection other than sight distance.

Design Issues

Bus stop design should guide alighting passengers to cross the road from behind the bus rather than from in front of the bus, which would enable passengers to see the oncoming traffic (*6*). In addition, pedestrians and commuters should be guided not to walk near the bus or cross the road by walking near the bus, because it is difficult for bus drivers to see pedestrians in these areas. Some mitigation strategies that improve sight distance and pedestrian visibility encourage commuters to walk in controlled areas that are easier for drivers to see. These mitigations include signing, striping, bus turnouts located such that alighting passengers have a clear view of the approaching traffic, crosswalks, and channelized pedestrian movement to crosswalks.

Cross References

Sight Distance Guidelines, 5-1
Methods to Increase Driver Yielding at Uncontrolled Crosswalks, 15-2

Key References

1. Campbell, B.J., Zegeer, C.V., Huang, H.H., & Cynecki, M.J. (2004). *A Review of Pedestrian Safety Research in the United States and Abroad.* (FHWA-RD-03-042). McLean, VA: FHWA.
2. Texas Transportation Institute, Texas A&M Research Foundation, and Texas A&M University (1996). *TCRP Report 19: Guidelines for the Location and Design of Bus Stops.* Washington, DC: Transportation Research Board.
3. Metcalf, D.D., & Bond, V.L. (2006). Bus stop guidelines to meet urban, suburban and rural conditions. *ITE 2006 Technical Conference and Exhibit Compendium of Technical Papers.*
4. Pecheux, K.K., Bauer, J.K., Miller, S., Rephlo, J.A., Saporta, H., Erickson, S., Knapp, S., & Quan, J. (2008). *TCRP Report 125: Guidebook for Mitigating Fixed-Route Bus-and-Pedestrian Collisions.* Washington, DC: Transportation Research Board.
5. Technology & Management Systems, Inc. (2001). *TCRP Report 66: Effective Practices to Reduce Bus Accidents.* Washington, DC: Transportation Research Board.
6. Pulugurtha, S.S., & Vanapalli, V.K. (2008). Hazardous bus stop identification: An illustration using GIS. *Journal of Public Transportation, 11*(2), 65-83.

CHAPTER 16

Special Considerations for Rural Environments

PASSING LANES

Introduction

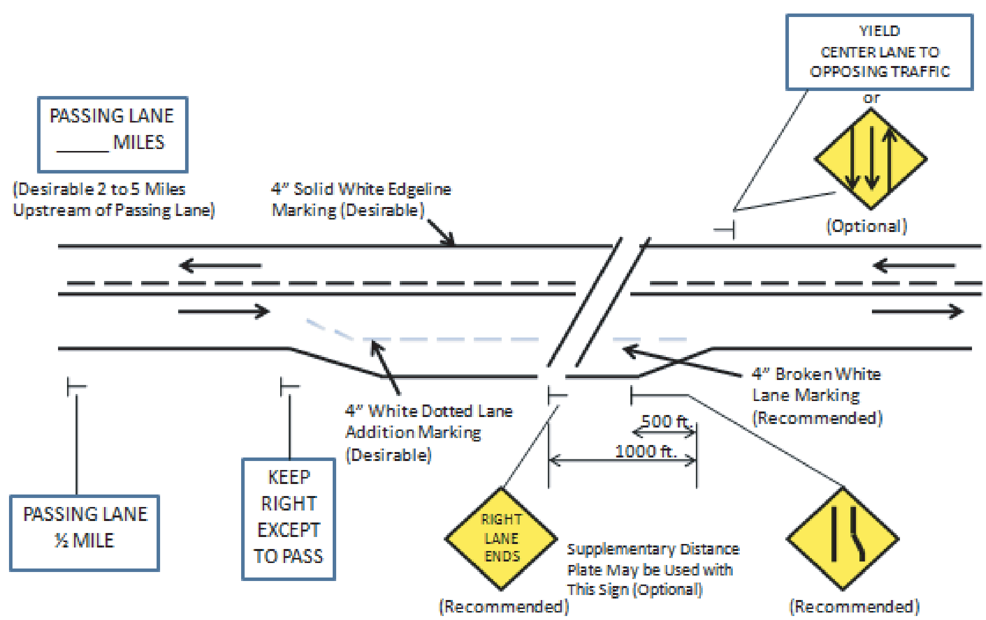
A passing lane is a lane added in one or both directions of travel on a two-lane, two-way highway to improve passing opportunities. This definition includes passing lanes in level or rolling terrain, climbing lanes on grades, and short four-lane sections (*1*). Passing lanes have been used mostly to allow drivers to bypass vehicles that are unable to maintain normal highway speeds on grades, usually called climbing lanes. Potts and Harwood (*2*) found that the primary benefit of passing lanes is the improvement of overall traffic operations on two-lane highways. This improved operation has direct implications for driver behavior because a driver stuck behind a slow-moving vehicle may be more likely to experience time delays and frustration, which could lead drivers to increase speeds to unsafe levels to pass a slow-moving vehicle.

Design Guidelines

RECOMMENDED VALUES OF LENGTH AND SPACING BY AVERAGE DAILY TRAFFIC (ADT) AND TERRAIN (*6*)

ADT (vpd)		Recommended Passing Lane Length (mi)	Recommended Distance between Passing Lanes (mi)
Level Terrain	Rolling Terrain		
≤ 1950	≤ 1650	0.8-1.1	9.0-11.0
2800	2350	0.8-1.1	4.0-5.0
3150	2650	1.2-1.5	3.8-4.5
3550	3000	1.5-2.0	3.5-4.0

TYPICAL PASSING LANE SIGNAGE AND MARKINGS (*3*)



Discussion

Two-lane highways with passing lanes provide a definite improvement in level of service over those without passing lanes (*2*). In particular, at medium and high volumes, a roadway with continuous alternating passing lanes can provide improvement by two levels of service over conventional two-lane highway without passing lanes. Similarly, a two-lane highway with less frequent passing lanes typically provides an improvement of one level of service over a conventional two-lane highway (*2*). Comparable improvements in service provided by passing lanes were found to reduce driver frustration and improve overall quality of service and the benefits of the passing lane extend beyond the confines of the added lane itself (*4*). Harwood, Hoban, and Warren (*3*) found that passing lanes improve the percentage of time drivers spend following other cars on those roads by 10% to 31% in comparison to a conventional two-lane highway without passing lanes. Passing lanes are generally well received by drivers; one study conducted in Kansas found that 93% of all respondents were positive about passing lanes and indicated a higher acceptance and satisfaction of the concept. Also, 46% of these drivers thought the passing lanes were just right in length, while 53% thought the passing lanes were too short (*5*). Mutabazi, Russell, and Stokes (*5*) also found that 88% of drivers agree more passing lanes are needed.

Highway engineers typically provide passing lanes with a primary objective of dispersing platoons and hence reducing travel time, with safety as a secondary objective. However, drivers view safety as the main benefit accrued from passing lanes (*5*). In the Kansas survey, 93% of drivers thought passing lanes improve safety, while 8% believed it encourages speeding. These driver perceptions are consistent with crash data analyses, which indicate that the installation of a passing lane on a two-lane highway reduces crash rates by approximately 25% (*3*). Harwood et al. (*3*) also found that crash frequency per mile per year within passing lanes sections on two-lane highways is 12% to 24% lower than for conventional two-lane highway sections.

Signage: Warning signs should be used to give drivers a preview of an upcoming passing lane and to warn drivers that the passing lane is ending. The safety and convenience benefits of passing lanes are reduced if passing lanes are not adequately signed. Clearly defined and well-maintained lane markings provide a similar function that can reduce the likelihood of drivers' selecting an oncoming lane in an attempt to enter or remain in a passing lane. In a survey of passing-lane signs, Wooldridge et al. (*6*) found that 61% of motorists prefer the wording "Left Lane for Passing Only" versus 29% who prefer "Keep Right Except to Pass." When surveyors reviewed the sign "Passing Lane Ahead 2 Miles," 61% of motorists would wait 2 mi to pass while the rest would pass when ready. This advance signing is useful because it also informs the driver of the repetitive nature of the passing lane design, allowing the driver to understand the purpose and nature of the roadway's characteristics. The sign should be used if the distance to the next passing lane is less than 12 mi. The sign "Right Lane End" is recommended to be located at a distance that will provide adequate notice that the passing lane is terminating.

Design Issues

Length: The effective length of the passing lane is defined as the physical length of the passing lane plus the distance downstream to the point where traffic conditions return to a level similar to that immediately upstream of the passing lane (*5*). Through computer stimulation, Harwood et al. (*3*) found the effective length to range between 4.8 km (3 mi) and 12.8 km (8 mi), depending on the physical length of the passing lane, traffic flow, traffic composition, and downstream passing opportunities.

Width and lane drop: Rinde (*7*) found the minimum width considered adequate for a two-lane road with a passing lane to be 40 ft. In the opinion of Rinde (*7*), passing should not be allowed for vehicles traveling in the single lane of three-lane roadways at traffic volumes above 3000 AADT. Also, the use of an appropriate lane-addition transition on the upstream end of a passing lane is needed for effective passing lane operations (*2*). The recommended length of this transition area is half to two-thirds of the length of the lane-drop taper (*2*).

Cross References

Signing Guidelines, 18-1
Marking Guidelines, 20-1

Key References

1. Mutabazi, M.I., Russell, E.R., and Stokes, R.W. (1999). Location and configuration of passing lanes. *Transportation Research Record, 1658*, 25-33.
2. Potts, I.B., and Harwood, D.W. (2004). *Benefits and Design/Location Criteria for Passing Lane.* Jefferson: Missouri Department of Transportation.
3. Harwood, D.W., Hoban, C.J., and Warren, D.L. (1988). Effective use of passing lanes on two-lane highways. *Transportation Research Record, 1195*, 79-91.
4. Hoban, C.J. and Morrall, J.F. (1986). *Overtaking Lane Practice in Canada and Australia* (ARR 144). Victoria: Australia Road Research Board.
5. Mutabazi, M.I., Russell, E.R., and Stokes, R.W. (1998). Drivers' attitudes, understanding and acceptance of passing lanes in Kansas. *Transportation Research Record, 1628*, 25-33.
6. Wooldridge, M.D., Messer, C.J., Heard, B.D., Raghupathy, S., Parham, A.H., Brewer, M.A., and Lee, S. (2001). *Design Guidelines for Passing Lanes on Two-Lane Roadways (Super 2)* (FHWA/TX-02/4064-1, TTI: 0-4064). College Station: Texas Transportation Institute.
7. Rinde, E.A. (1977). *Accident Rates vs. Shoulder Width: Two-Lane Roads, Two-Lane Roads with Passing Lanes* (CA-DOT-TR-3147-1-77-01). Sacramento: California Department of Transportation.

COUNTERMEASURES FOR PAVEMENT/SHOULDER DROP-OFFS

Introduction

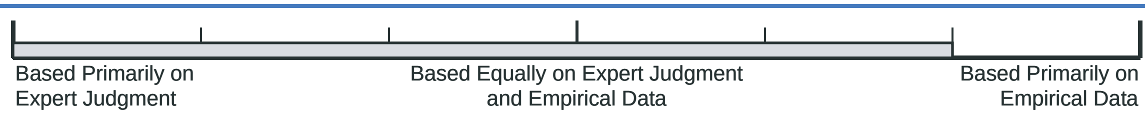
A shoulder is a portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles, for emergency use, and for lateral support of the sub-base, base, and surface courses. The roadway shoulder has been recognized as desirable ever since engineers began paving roadways. However, the width, uniformity, and stability of roadway shoulders have varied greatly from roadway to roadway and along different sections of the same roadway (*1*). Shoulders on rural roadways serve as structural support for the surfacing and additional width for the traveled way. Shoulder drop-offs occur when there is a difference in height (ranging from a fraction of an inch to several inches) between the pavement surface and the roadside surface (*2*). This height difference typically arises from tire rutting erosion, excessive wear, or resurfacing. The primary concern related to drop-offs is that if they are too high, then it can pose a crash risk if a vehicle drifts outside the road and has a wheel go over the drop-off.

Design Guidelines

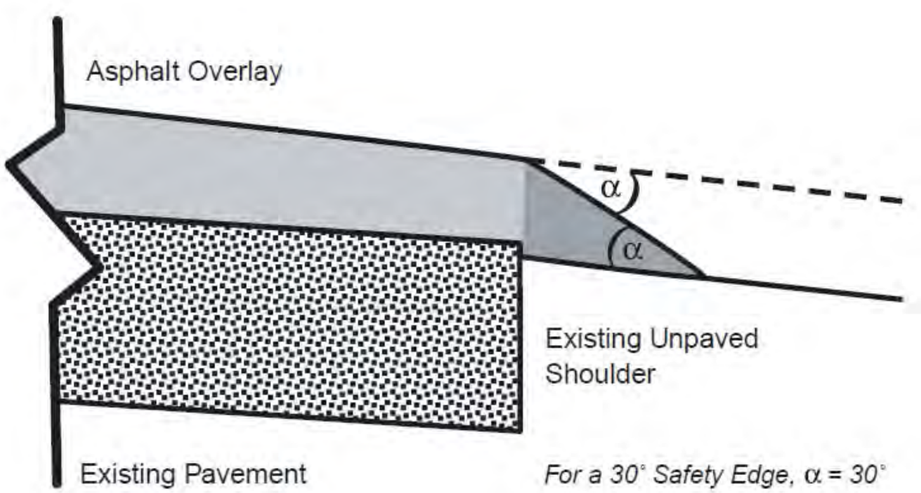
Vertical or near-vertical shoulder drop-off heights that exceed the indicated table values warrant consideration for drop-off treatment or traffic control (in work zones; adapted from Graham & Glennon (*3*)).

VERTICAL DROP-OFF HEIGHT WARRANTING TRAFFIC CONTROL FOR VARIOUS LANE WIDTHS

Speed (mi/h)	Drop-off Height			
	12-ft Lane Width	11-ft Lane Width	10-ft Lane Width	9-ft Lane Width
30	3 in.	3 in.	3 in.	2 in.
35	3 in.	3 in.	2 in.	1 in.
40	3 in.	2 in.	1 in.	1 in.
45	2 in.	1 in.	1 in.	1 in.
≥ 50	1 in.	1 in.	1 in.	1 in.



EXAMPLE OF SAFETY EDGE RECOMMENDED BY THE FHWA (*4*)



Discussion

A primary safety concern related to drop-off from the perspective of driver performance occurs when a vehicle leaves the lane and has a tire go over the drop-off (typically the front right tire). This event is often surprising and unfamiliar for most drivers, and a drop-off can interfere with their ability to return the vehicle safely to the lane. In particular, if drivers try to return to the lane at high speed and at low steering angles, their tire can "scrub" against the drop-off edge, impeding their return. A common response is to increase the steering angle towards the lane, which can lead to an abrupt change in heading once the drop-off is overcome. In severe cases, this response can result in a vehicle swerving out of the lane into the opposite-direction travel lane, putting the driver at risk of a collision with an oncoming vehicle. Motorcyclists can also have difficulties traversing drop-offs, although the vehicle control issues are somewhat different. Crash data analyses suggest that the overall frequency of crashes "probably" or "possibly" related to high drop-off is relatively low (less than 3% of rural road crashes for related road types), but that these crashes tend to result in a greater proportion of fatalities or injuries than typical rural road crashes (*4*).

The guideline information is primarily based on an analysis of drop-offs for work zones (*3*). The original source table also contained drop-off height thresholds that were higher than 3 in., but these were changed in the current guideline to reflect a more conservative assessment of other related driver performance data on driver encounters with drop-offs of various heights (*4*). Note that the recommendation only represents general guidance related to driver performance; other sources—such as the *Roadside Design Guide* (*5*)—recommend that vertical drop-offs with differentials of 2 in. or more should be avoided. What the guideline table is intended to convey is that vertical drop-off heights that exceed the listed values are more likely to be associated with increased difficulty for drivers trying to recover in a controlled manner if one of their tires go over the drop-off edge.

Another design aspect related to drop-offs that affects driver performance is the shape of drop-off. In particular, safe return to the lane is significantly more successful if a tire had to overcome a drop-off with a slope of 45° or shallower. The figure accompanying the guideline illustrates the relative "safety" of three drop-off geometries. Lane recovery with a sloped or filleted drop-off is significantly better than a straight vertical or curved drop-off. Moreover, the effectiveness of sloped drop-offs persists at higher speeds and at higher drop-off heights (*4*).

Design Issues

There are several accepted approaches for addressing drop-offs that are too high. For example, in work zones MUTCD warning signs for edge drop-off can notify users of present drop-off conditions. The application of a wedge-shaped asphalt material called "Safety Edge" is another possible countermeasure (see figure on previous page). When placed between the roadway and the shoulder, the material can help drivers recover from the shoulder to the driving surface. The asphalt material needs to be compacted to increase strength, otherwise the material will break apart over time due to forces and runoff water. Graham, Richard, and Harwood (*6*) found the results of empirical Bayes and cross-sectional analysis of sites paved with and without Safety Edge reveal that the material has a net positive effect on the safety of rural highways. Humphreys and Parham (*1*) found that the shoulder is best resurfaced when the roadway is resurfaced so that shoulder drop-off does not form. They also recommend that the contractor, in areas where road-resurfacing contracts must be bid separately, should be required to provide a 45° angle fillet along the edge of the roadway as part of the scope of work.

Cross References

Design Consistency in Rural Driving, 16-8

Key References

1. Humphreys, J.B., and Parham, J.A. (1994). *The Elimination or Mitigation of Hazards Associated with Pavement Edge Drop-offs During Roadway Resurfacing.* Washington, DC.: AAA Foundation for Traffic Safety.
2. Fitzpatrick, K., Parham, A.H., and Brewer, M.A. (2002). *Treatments for Crashes on Rural Two-Lane Highways in Texas* (FHWA/TX-02/4048-2). College Station: Texas Transportation Institute.
3. Graham, J.L., and Glennon, J.C. (1984). *Work Zone Design Considerations for Truck Operations and Pavement/Shoulder Drop-offs.* Washington, DC: FHWA.
4. Hallmark, S.L., Veneziano, D., McDonald, T., Graham, J., Bauer, K.M., Patel, R., and Council, F.M. (2006). *Safety Impacts of Pavement Edge Drop-Offs.* Washington, D.C.: AAA Foundation for Traffic Safety.
5. AASHTO (2002). *Roadside Design Guide.* Washington, DC.
6. Graham, J.L., Richard, K.R., and Harwood, D.W. (2009). *Safety Evaluation of Safety Edge Treatment—Year 2, Interim Report.* Kansas City, MO: Midwest Research Institute.

RUMBLE STRIPS

Introduction

Shoulder rumble strips (SRS) are raised or grooved patterns on the shoulder of a travel lane intended to provide a tactile/haptic and auditory alert to drivers who stray onto the shoulder. When a vehicle's wheels traverse an SRS, they generate both an increase in sound and haptic (physical) vibrations that drivers feel through their seat, foot pedals, floor, and steering wheel. SRSs are best suited for warning inattentive or drowsy drivers who are leaving the travelled way. SRSs can potentially wake drivers who fall asleep; however, this result typically requires a greater level of sound and vibration. In general, SRSs must produce sound and vibration levels that are easily detectable, yet not so loud and jarring that they startle drivers. The design challenge is balancing the need to provide alerts in a variety of situations (e.g., in heavy trucks or to sleeping drivers) with the need to avoid potentially undesirable startling effects and difficulties that SRSs can cause bicyclists.

Previous safety evaluations of SRSs confirm their overall effectiveness. For example, Griffith (*1*) indicates there is a medium-high level of predictive certainty that SRSs reduce all single-vehicle run-off-road (SVROR) crashes by 21% on rural freeways and by 18% on all freeways (i.e., both rural and urban). NCHRP research (*2*) also indicates that continuous SRSs reduce injury SVROR crashes by 7% on rural freeways and by 13% on all freeways. Rumble strips have been shown to significantly reduce the run-off-road crash rate on some rural highways by up to 80% (*3*).

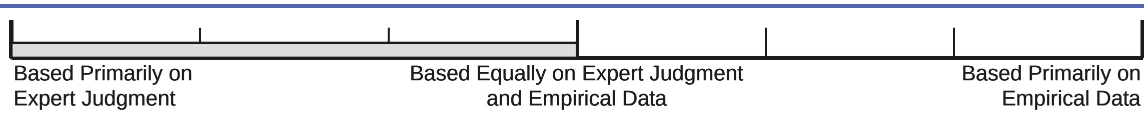
Design Guidelines

COMMON ROADWAY SOUNDS AND ASSOCIATED dB LEVELS

SRS should produce an audible sound between 6 and 15 dB louder than background noise levels.	dB	Sound	dB	Sound
	60	Freeway driving from inside car	85	Heavy traffic
	70	Freeway traffic	90	Truck
	75-80	Inside heavy truck cab	95-100	Motorcycle
	85	City traffic inside car	110	Car horn

EFFECTS OF DIFFERENT SRS DIMENSIONS ON AUDITORY / TACTILE ALERTS

Characteristic	Suitable Values	Direct Effect on Driver	Implications for Effectiveness
Lateral placement / offset	• 6+ in. from lane edge (but depends on other factors)	Drivers encounter the alert sooner, the closer it is to the lane edge.	The sooner the warning occurs, the more space drivers have to recover before reaching the road edge.
Groove Width	• 16 in. (12 may be acceptable if the shoulder is narrow)	Wider SRS will produce sounds/vibrations for a longer duration as the vehicle laterally traverses it.	Sounds presented for longer durations are generally easier to detect.
Groove Depth	• 7/16 in.	Deeper grooves increase sound and vibration alert levels.	Louder sounds and vibrations are easier to detect relative to background noise levels.
Groove Separation	• 11-12 in.	Narrower groove separation slightly increases the frequency.	Drivers generally perceive higher tones as sounding more urgent.
Longitudinal Gaps	• None if shoulder not shared with bikes • 12 ft if shoulder shared with bikes	Gaps of 12 ft or less can reduce the chance that a vehicle will miss the SRS completely.	Effectiveness will be lower than without gaps because alert duration will be shorter over gap sections.



Discussion

Torbic et al. (*4*) found that there is no conclusive evidence indicating a clear minimum level of stimulus that a shoulder or centerline rumble strip must generate in order to alert an inattentive, distracted, drowsy, or fatigued driver. However, the applicable research literature generally indicates that rumble strips that generate a 3 to 15 dBA increase above the ambient in-vehicle sound level can be detected by awake drivers. Also some evidence suggests that a sudden change in sound level above 15 dBA could startle a driver. However, a rumble strip generating more than a 15 dBA increase above the ambient sound level should not be automatically assumed to cause negative impacts (e.g., an increase in crashes), but rather to increase the potential for startling drivers who encounter the rumble strip.

Related guidance for in-vehicle warning tones typically recommends sound intensity levels for auditory-only warnings (unaccompanied by vibrations) of between 10 and 30 dB above background noise levels, while not exceeding 90 dB overall. The SRS guidelines differ significantly from the guidance for in-vehicle warning tones because of the presence of haptic vibrations with the SRS. In particular, at least for passenger vehicles, background vibration levels are low in small vehicles and even a small change in vibration can be clearly detected. Laboratory driving simulator studies show that usually drivers easily detect steering wheel or brake pedal vibrations of 1.2-1.5 N • m torque presented over half a second. In contrast to passenger vehicles, cab vibrations in heavy trucks are significant and the size and weight of heavy trucks reduce the vibrations generated by SRS; therefore, the vibration component of SRS is viewed to have minimal benefit for alerting heavy truck drivers.

It is also worth noting that the effectiveness of SRS for waking sleeping drivers has not been closely examined and that it is likely that SRS are much less effective in this application. The primary reasons for this lesser effectiveness are that greater stimulus levels are required to wake a sleeping driver rather than to merely alert a distracted or drowsy driver and that the increased arousal caused by traversing rumble strips is brief and insufficient (*5*).

The rationale for the "suitable values" in the guidelines table is discussed in further detail in FHWA (*6*), Spring (*7*), and Torbic et al. (*4*). For the most part, the values also accommodate bicycle traffic on the shoulder.

Design Issues

An important consideration when installing SRS on non-controlled-access roadways is the impact on bicyclists (and possibly motorcyclists) because several aspects that improve the alerting aspects of rumble strips (e.g., depth) also make SRS more challenging to traverse. A key factor in the suitability of a shoulder for accommodating both SRS and bicycle traffic is the shoulder width (see table below). Bicyclists also need gaps at sufficient frequency to cross the rumble strips in advance of hazards or intersections. Moeur (*8*) suggests a 12-ft gap in 60-ft cycle, which will result in 80% coverage of the shoulder with rumble strips and exactly 1½ times cycle length for lane line striping. Other options are to use a 40-ft cycle, consisting of a 28-ft long rumble strip with a 12-ft gap, though the 40-ft cycle will provide gaps more frequently for a given speed.

Shoulder Width (ft)	Is there a Problem?	Reasoning
0-1.9	No	Shoulder is too narrow for SRS or bicyclists.
2-3.9	Yes	Shoulder may be wide enough for SRS or bicyclists.
4-5.9	Yes	Shoulder may be wide enough for both SRS and bicyclists.
6+	No	Shoulder is wide enough for SRS and bicyclists.

Cross References

Countermeasures for Pavement/Shoulder Drop-offs, 16-4

Key References

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DESIGN CONSISTENCY IN RURAL DRIVING

Introduction

Design consistency refers to the conformance of a highway's geometric and operational features with driver expectancy (*1*). All other factors being equal, drivers will make fewer errors when faced with geometric features that are consistent with their expectations. Note that the guideline information below only provides general information about some of the factors associated with the concept of design consistency. Although research suggests that the factors listed are relevant to design consistency, at this time there is insufficient data to provide detailed quantitative recommendations.

Design Guidelines

The following driver expectancies (adapted from Lunenfeld & Alexander (*2*)) and factors (adapted from Fitzpatrick et al. (*3*)) should be considered in a design consistency review.

What is known about driver expectancies?	What factors should be considered in a design consistency review?
1. Drivers tend to anticipate upcoming situations and events that are common to the road that they are traveling. 2. The more predictable the roadway, the less likely there will be driver errors. 3. Drivers experience problems when surprised or with inconsistent design or operation. 4. Drivers generally assume they will only have to react to standard situations. 5. The roadway and its environment *upstream* of a site create expectancy for *downstream* conditions. 6. Expectancies are associated with all levels of driving performance and all aspects of the driving situation.	• Cross-section markings • Guide signs and route markers • Warning and regulatory signs • Geometry • Sight distance • Road type and surface • Signals • Lighting Consider also: • Land use • Terrain • Typical traffic conditions • Typical weather More detailed analyses can be conducted for: • Navigation expectancies • Guidance expectancies • Special geometric and other features

Discussion

As noted on the previous page, design consistency refers to the conformance of a highway's geometric and operational features with driver expectancy (*1*). In a key study leading to the development of the Interactive Highway Safety Design Model (IHSDM), crash and field data were analyzed and speed prediction models were developed for a variety of different roadway alignments (*3*). Four design consistency measures were associated with crash frequency:

1. Predicted speed reduction on a horizontal curve relative to the preceding curve or tangent (has the strongest and most sensitive relationship to crash frequency)
2. Ratio of an individual curve radius to the average radius for the roadway section as a whole
3. Average rate of vertical curvature on a roadway section
4. Average radius of curvature on a roadway section

Design consistency is an important concept because the driving task requires continuous/frequent:

- Sampling of visual, auditory, and haptic (touch or feel) cues
- Processing of these cues and decision making
- Outputs in the form of steering, brake, and accelerator inputs

This requirement to continuously "perceive–think–act" takes considerable effort (even when some activities become more or less automated), especially under challenging circumstances such as poor weather, nighttime conditions, heavy traffic, high speeds, etc. Inconsistent roadway design has the potential for increasing driver uncertainty about—for example—where to look for signs, how much illumination to expect from roadway section to roadway section, and how fast to drive. An inability to anticipate and predict the conditions that shape driving decisions and behaviors can lead to higher workload and, ultimately, decrements in driving performance and safety. Thus, minimizing driver workload through consistent layout and alignment of roadways is an important design goal. Although driver expectancies for a roadway can vary widely with respect to their completeness and correctness, there should ideally be a reasonable match between the geometric and operating characteristics of the rural driving environment and the driver's expectancies for this environment.

The underlying psychological factor supporting the need for design consistency is the notion of mental models or schemas (see Gentner & Stevens (*4*)), which—broadly defined in the context of system design—is the user's internal understanding and representation of an external reality. In the driving environment, one type of mental model is the driver's understanding of the roadway and the surrounding infrastructure, how the roadway system works, and how to operate within it. A key aspect of mental models is that they allow the driver to predict the outcome of his or her driving behaviors.

Design Issues

The IHSDM is a suite of software analysis tools for evaluating safety and operational effects of geometric design decisions on two-lane rural highways. IHSDM is a decision support tool that checks existing or proposed two-lane rural highway designs against relevant design policy values and provides estimates of a design's expected safety and operational performance. FHWA's website for the IHSDM can be found at http://www.tfhrc.gov/safety/ihsdm/ihsdm.htm.

Cross References

Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems, 17-14

Key References

1. Wooldridge, M.D., Fitzpatrick, K., Harwood, D.W., Potts, I.B., Elefteriadou, L., and Torbic, D.J. (2003). *NCHRP Report 502: Geometric Design Consistency on High-Speed Rural Two-Lane Roadways.* Washington, DC: Transportation Research Board.
2. Lunenfeld, H., and Alexander, G. J. (1984). Human factors in highway design and operations. *Journal of Transportation Engineering, 110*(2), 149-158.
3. Fitzpatrick, K., Elefteriadou, L., Harwood, D.W., Collins, J.M., McFadden, J., Anderson, I B., et al. (2000). *Speed Prediction for Two-Lane Rural Highways* (FHWA-RD-99-171, Final Report). McLean, VA: FHWA.
4. Gentner, D. and Stevens, A.L. (Eds.) (1983). *Mental Models.* Hillsdale, NJ: Lawrence Erlbaum Associates.

CHAPTER 17

Speed Perception, Speed Choice, and Speed Control

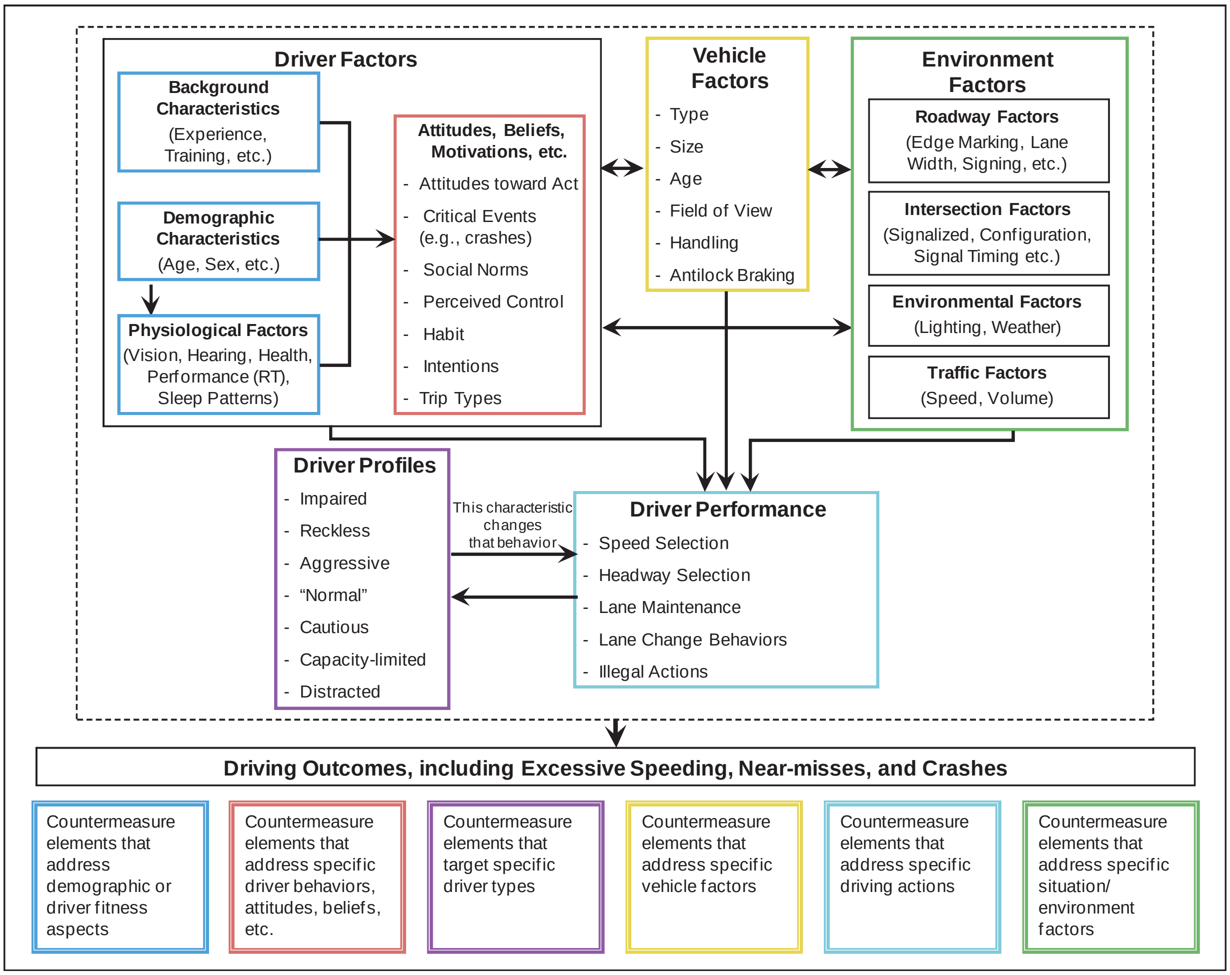
BEHAVIORAL FRAMEWORK FOR SPEEDING

Introduction

Behavioral framework for speeding refers to a conceptual overview of the key factors relevant to speed selection, as well as their relationship to potential speeding countermeasures. The figure below provides such a framework and attempts to capture the relevant driver, vehicle, roadway, and environment (DVRE) factors and to link these "predictor variables" to specific indices of driver behavior and driver performance. The factors and relationships depicted in the figure are firmly grounded in relevant studies and analyses of driver behavior. Specifically, it reflects past analyses and syntheses of the research literature on driver behavior and crash risk (*1*, *2*), recent run-off-road safety work (*3*), safety countermeasures (*4*, *5*), results from the recent 100-car study conducted by VTTI (*6*), as well as research that covers driving or crashes more generally (e.g., *7*, *8*, *9*). Importantly, the framework includes a variety of countermeasure types, explicitly targeted at specific DVRE interactions.

Design Guidelines

Countermeasures intended to address speeding should consider the following representation of speed selection to fully understand the relative roles of situation, demographics, individual differences, and unexplained variance in predicting travel speeds.



Discussion

A substantial amount of research has been done on the causes of speeding and it is clear that speeding is a complex driving behavior. There is typically no single simple solution for addressing speeding concerns. The table below shows the multitude of factors that have been found to be associated with speeding or speed-related crashes. Despite all this research, there is still uncertainty regarding the relative importance of these factors and how this information can be used to develop countermeasures that effectively target specific types of drivers. The figure shown as part of the guideline on the previous page depicts how several of these factors' corresponding countermeasures are related.

FACTORS FOUND TO BE ASSOCIATED WITH SPEEDING IN PREVIOUS RESEARCH

Factor	Example Variables	Example References (see Chapter 23 for full citations)
Demographic	Age, gender, socioeconomic and education level	DePelsmacker & Janssens, 2007; Harré, Field & Kirkwood, 1996; Hemenway & Solnick, 1993; Stradling, Meadows & Beatty, 2002
Personality	Attitudes, habits, personal and social norms, thrill-seeking, beliefs	Arnett, Offer & Fine, 1997; Clément & Jonah, 1984; DePelsmacker & Janssens, 2007; Ekos Research Associates, 2007; Gabany, Plummer & Grigg, 1997; McKenna & Horswill, 2006; Stradling, Meadows & Beatty, 2002
Roadway	Posted speed	Book & Smigielski, 1999; Giles, 2004
Environment	Urban/rural	Giles, 2004; Rakauskas, Ward, Gerberich & Alexander, 2007
Vehicle	Engine size; vehicle age	Hirsh, 1986; Stradling, Meadows & Beatty, 2002
Risky Behaviors	Drinking and driving, seatbelt use, red light running	Arnett, Offer & Fine, 1997; Cooper, 1997; Gabany, Plummer & Grigg, 1997; Harré, Field & Kirkwood, 1996; Hemenway & Solnick, 1993; Rajalin, 1994
Situational	Trip time, mood, inattention, fatigue	Arnett, Offer & Fine, 1997; Ekos Research Associates, 2007; Gabany, Plummer & Grigg, 1997; Hirsh, 1986; McKenna, 2005; McKenna & Horswill, 2006

Design Issues

None.

Cross References

Speeding Countermeasures: Setting Appropriate Speed Limits, 17-10
Speeding Countermeasures: Communicating Appropriate Speed Limits, 17-12
Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems, 17-14

Key References

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8. Groeger, J.A. (2000). *Understanding Driving: Applying Cognitive Psychology to a Complex Everyday Task*. Hove, U.K.: Psychology Press.
9. Treat, J.R., Tumbas, N.S., McDonald, S.T., Shinar, R.D., Mayer, R.E., Sansifer, R.L., et al. (1979). *Tri-level Study of the Causes of Traffic Accidents, Executive Summary* (DOT HS 805 099). Bloomington: Indiana University.

SPEED PERCEPTION AND DRIVING SPEED

Introduction

Speed perception refers to a driver's judgment of how fast he or she is traveling. While direct speed information is available from the speedometer, drivers still rely heavily on cues from the environment to judge how fast they are traveling. Auditory (engine noise) and tactile (vibrations) information can influence speed perception; however, drivers' primary basis for estimating their speed is the visual sensation provided by the highway geometrics and other information about objects in their immediate environment streaming through their visual field. If drivers underestimate their travel speed, they are traveling faster than they expect, and if they overestimate their travel speed, they will travel slower than they expect.

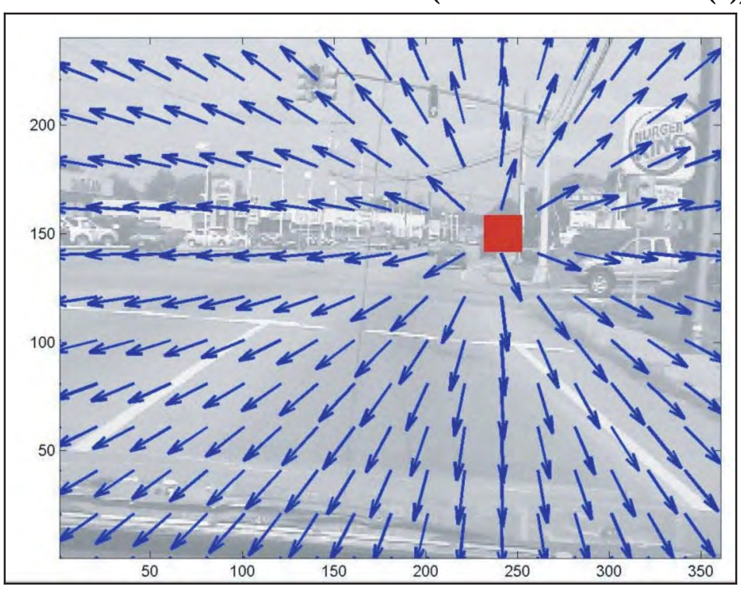
Design Guidelines

- The driver's perceptual experience of the roadway should be consistent with intended travel speed.
- There should be some consistency between relevant roadway cues and posted speeds.

FACTORS THAT AFFECT SPEED PERCEPTION

Factors that May Cause Drivers to UNDERESTIMATE Their Travel Speed	Factors that May Cause Drivers to OVERESTIMATE Their Travel Speed
• Higher design standard • Greater roadway width • Divided, walled urban roads • Rural roads without roadside trees • Daylight compared to nighttime illumination conditions	• Two-lane narrow urban roads • Roads densely lined with trees • Transverse pavement markings

GRAPHICAL EXAMPLE OF OPTIC FLOW FROM A CENTRAL FOCAL POINT, WHICH IS INDICATED AS THE RED BOX (FROM CNS VISION LAB (*1*))



Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

Discussion

In Fildes, Fletcher, and Corrigan (*2*), subjects viewed film presentation of moving scenes in a laboratory setting. The study was conducted to develop a suitable means of assessing the sensory perception of speed on the road and to evaluate the effects of several road and roadside features on the speed judgments of drivers. Among other findings, the researchers reported that drivers underestimated their travel speeds on roads with higher design standards, on roads with a greater width, on divided and wide urban roads, and on rural roads without roadside trees (compared to those with many trees). They tended to overestimate their speeds on two-lane narrow urban roads.

In Triggs and Berenyi (*3*), subjects estimated speed under day and night conditions as passengers driving in a car on an unlit freeway. Speed was underestimated in both day and night conditions; however, judgments were more accurate at night than during the day. Importantly, centerline pavement-mounted reflectors provided a highly visible feature that was unavailable during the day.

From three types of speed estimation—(1) a driver's estimate of his/her own vehicle speed, (2) the estimation of approaching vehicle speed, and (3) detection of relative velocity when car-following—Triggs (*4*), a broad review of speed estimation studies, shows the following trends:

- Speed perception increases when transverse stripes are painted across the road with their separation progressively decreasing (though they may be effective only for drivers who are unfamiliar with the site).
- Speed judgments tend to be higher when a rural road is lined with trees.
- Speed judgments tend to be higher in low light conditions.
- During car-following, judgments of relative speed tend to be made more accurately when the gap between the two vehicles is closing rather than when it is opening.
- When car-following, observers in the following car tend to underestimate the relative speed difference between their car and the one in front of it.

The figure on the previous page illustrates two important sources of information that underlie drivers' speed perception. The first is the point of expansion, which is denoted by the red square, and the second is the optic flow, which is shown as the blue arrows. During forward motion, the point of expansion indicates the observers' destination and appears stationary relative to the observer. All other points are seen as moving away from the point of expansion, and the relative motion of the optic flow points forms the basis for speed perception. Points that are closer to the observer appear to move faster than points closer to the point of expansion. Stronger and more consistent optic-flow cues (e.g., dense/cluttered visual environments, salient pavement marking, etc.) can amplify the sensation of speed through the environment and cause higher speed judgments.

Design Issues

Speed adaptation, which occurs for drivers who continue at a constant speed for an extended period of time, leads to drivers generally underestimating their speed in latter sections of extended tangent sections (*4*). This adaptation effect has implications for design elements requiring speed changes, such as horizontal curves, because drivers may be traveling faster than expected. Additionally, this effect may also carry over to nearby roadways (*5*). Milosevic and Milic (*6*) investigated the accuracy of speed estimation in sharp curves and the effect of advisory signs on speed estimation and found that drivers with over 11 years of experience significantly underestimated their speeds.

Cross References

Behavioral Framework for Speeding, 17-2
Effects of Roadway Factors on Speed, 17-6
Effects of Posted Speed Limits on Speed Decisions, 17-8

Key References

1. CNS Vision Lab (n.d.) *Heading Perception: Where Am I Going?* Retrieved November 24, 2009 from http://cns.bu.edu/visionlab/projects/buk/
2. Fildes, B.N., Fletcher, M.R., and Corrigan, J.M. (1987). *Speed Perception 1: Drivers' Judgements of Safety and Speed on Urban and Rural Straight Roads.* (CR 54). Canberra, Australia: Federal Office of Road Safety.
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4. Triggs, T.J. (1986). Speed estimation. In G.A. Peters & B.J. Peters (Eds.), *Automotive Engineering and Litigation* (pp. 95-124). New York: Garland Press.
5. Casey, S.M., and Lund, A.K. (1987). Three field studies of driver speed adaptation. *Human Factors, 29*(5), 541-550.
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EFFECTS OF ROADWAY FACTORS ON SPEED

Introduction

The *effects of roadway factors on speed* refers to the impact of geometric, environmental, and traffic factors on driving speed under free-flow conditions in tangent roadway sections. Speed in curve entry is covered in Chapter 6. Free-flowing speed is defined as conditions in which a driver has the ability to choose a speed of travel without undue influence from other traffic, conspicuous police presence, or environmental factors. In other words, the driver of a free-flowing vehicle chooses a speed that he or she finds comfortable on the basis of the appearance of the road. Typically this involves a minimum headway time of 4 to 6 s (*1*). Note that although posted speed is often found to be one of the factors that is most strongly correlated with free-flow speed, this correlation is somewhat misleading, because driver compliance with posted speed can be low if the posted speed is set too low (see the guideline "Effects of Posted Speed Limits on Speed Decisions," on page 17-8). In contrast, the strong association between posted speed and free-flow speed typically occurs because the 85th percentile speed is often used to set the posted speed limit.

Design Guidelines

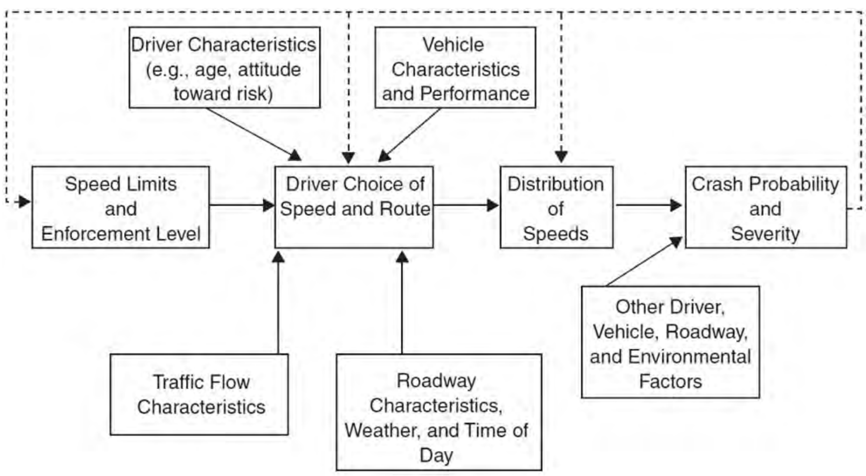
The following factors that appear to be associated with drivers' choosing a higher travel speed should be considered when designing roadways.

Factors Associated with HIGHER Free-Flow Speeds	Strength of Empirical Evidence	
	Rural Highways	Low-Speed Urban Streets
Higher Design Speed	Solid	Solid
Grade	Solid	Solid
Wider Lane Width	—	Mixed
Higher Access Density	Solid	Mixed
Separated Bicycle Lanes	—	Mixed
Less Pedestrian/Bicycle Side Friction	—	Mixed
No Roadside Parking	—	Mixed
Number of Lanes	Solid	—
Shoulder Width	Mixed	—

Discussion

As the table on the previous page makes clear, the empirical record is far from conclusive with respect to the ability to predict drivers' speed choices associated with relevant geometric, environmental, and traffic factors. Nonetheless, some relationships between drivers' speed choices and these factors—however tentative—have emerged from the literature and are worth presenting here. Currently, there is insufficient research to provide more quantitative guidance about how much the factors listed in the guideline table increase free-flow speed.

As seen in the figure below, roadway factors impact both the driver's choice of speed, as well as overall crash probability and severity. In Fitzpatrick, Carlson, Brewer, and Wooldridge (*3*), data were collected at 24 horizontal curve sites and 36 straight section sites to identify roadway factors that influence speed. Data collected included details of alignment (e.g., curve radius, curve length, straight section length), cross section (e.g., lane width, superelevation, median characteristics), roadside details (e.g., access, density, pedestrian activity), and information on traffic control devices. Laser guns were used to collect speed from vehicles at the 60 (total) sites. Multiple regression techniques, using 85th percentile speed as a "quantifiable definition of operating speed," were used in the analysis. The alignment (downstream distance to control) and cross section (lane width) factors explained about 25% of the variability in the speed data for both curve and straight road sections. Roadside factors were not significant for the straight road sections, but accounted for about 40% of the variability in the speed data for curves. Additional analyses conducted without using posted speed limits resulted in only lane width as a significant variable for straight road sections, with both median presence and roadside development as significant variables for curves.



Source: Milliken, J.G., Council, F.M., Gainer, T.W., Garber, N.J., Gebbie, K.M., Hall, J.W., et al. (*2*)

Design Issues

None.

Cross References

Design Consistency in Rural Driving, 16-8
Behavioral Framework for Speeding, 17-2

Key References

1. Parker, M.R., Jr. (1997). *Effects of Raising and Lowering Speed Limits on Selected Roadway Sections.* (FHWA-RD-92-084). McLean, VA: FHWA.
2. Milliken, J.G., Council, F.M., Gainer, T.W., Garber, N.J., Gebbie, K.M., Hall, J.W., et al. (1998). *Special Report 254: Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits*. Washington, DC: Transportation Research Board.
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EFFECTS OF POSTED SPEED LIMITS ON SPEED DECISIONS

Introduction

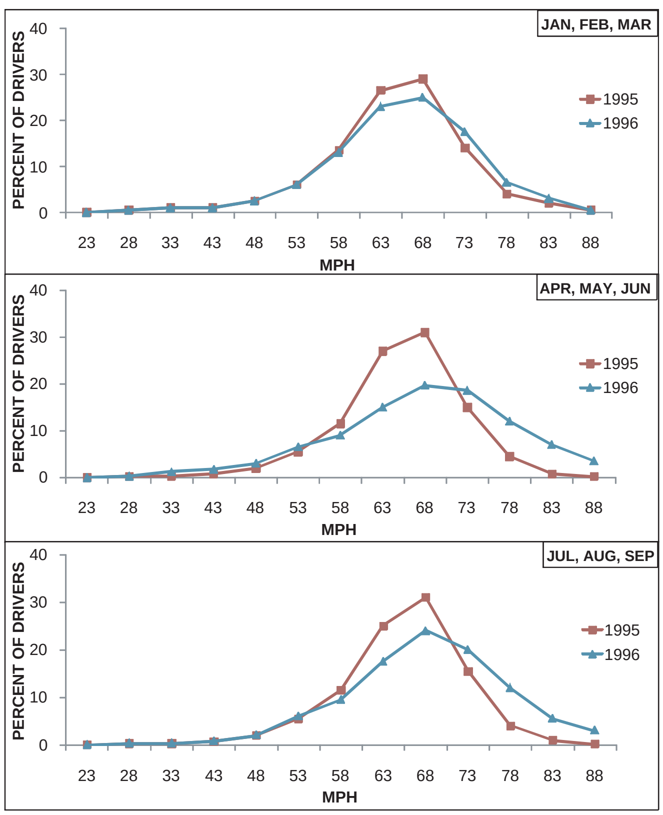
The *effects of posted speed limits on speed decisions* refers to the impact that posted speed has on actual speeds selected by drivers. This guideline covers light-vehicle driver compliance with posted speed limits on non-limited-access rural and urban highways. Drivers are legally in compliance when they are traveling at or below the posted speed limit. At a practical level, however, drivers are typically given—and they expect to be given—some small margin above the posted speed limit before being subject to law enforcement (*1*). Driver compliance is best assessed under free-flow conditions for a roadway segment because driver speed behavior is then largely unconstrained by external influences (e.g., traffic congestion, road work, or extreme weather) and they are free to choose their "natural" speed based on the roadway.

Design Guidelines

Posted speed limits should not be used as the only method to limit free-flow speed in light vehicles.

- For most urban and rural highways, increasing or decreasing the posted speed limits changes 85th percentile speed by approximately 1 to 2 mi/h in the same direction as the change.
- For interstate freeways, increasing the posted speed limits increases 85th percentile speed by approximately 1 to 3 mi/h. Speed dispersion also increases.

The figure below shows daytime traffic speed distributions and illustrates driver-selected speed relative to posted speed, as well as overall speed dispersion. The data are from interstate highways in Montana, both before (1995 data, 55 mi/h posted speed) and after (1996 data, at least 70 mi/h posted speed) the repeal of the National Maximum Speed Limit (NMSL) law (effective December 8, 1995).



Source: recreated from Milliken et al. (*2*)

Discussion

It is quite clear from both everyday observation and existing research data that most drivers do not comply with posted speed limits. In Harkey, Robertson, and Davis (*3*), data were collected and analyzed from 50 locations in four states to determine travel speed characteristics. The authors reported that 70.2% of drivers did not comply with posted speed limits, specifically (1) 40.8% exceeded posted speed limits by more than 5 mi/h; (2) 16.8% exceeded posted speed limits by more than 10 mi/h; and (3) 5.4% exceeded posted speed limits by more than 15 mi/h.

Milliken et al. (*2*) conducted a broad review of current practices in setting speed limits and provided guidelines to state and local governments on appropriate methods of setting speeds limits and related enforcement strategies. With respect to driver perceptions of speeding and speed limits, the review found that (1) most drivers do not perceive speeding as a particularly risky activity; (2) most drivers will drive at what they consider an appropriate speed regardless of the speed limit; and (3) advisory speeds have modest to little effect on driver speed, particularly for drivers who are familiar with the road. Taken together, these attitudes result in generally low compliance with posted speed.

Also from Milliken et al. (*2*), changing speed limits does not always result in the intended changes in behavior. Lowering the speed limits on major highways reduced both travel and speed fatalities, although driver speed compliance gradually eroded. Drivers violate new, higher speed limits because they expect the same enforcement tolerance of 5 to 10 mi/h at the higher limits. Specifically, average and 85th percentile speed typically increased 1 to 3 mi/h despite larger increases in the speed limit—a minimum of 5 mi/h. Parker (*4*) also found that increasing or reducing the posted speed on urban and rural non-limited access roadways did not significantly change the number of injury or fatal crashes.

Overall, changes in speed limits seem to simply legalize existing driver behavior; that is, they change compliance levels rather than speeding behavior. The findings suggest the difficulty of altering behavior merely by changing a speed sign.

As noted elsewhere, speed choices are clearly mediated by a number of factors. Milliken et al. (*2*) found evidence that speed enforcement is the most common mediator between speed limit and speed choice. Where speed choice is not constrained by speed limits and their enforcement, the driver does trade off travel time and safety. In an analysis of FHWA data, Uri (*5*) found that adherence to the 55 mi/h limit does depend on the time cost of travel, cost in terms of discomfort and irritability, enforcement and, for a subset of states, the price of gasoline.

Design Issues

One design issue to consider when changes to the posted speed limit are contemplated is the possibility of speed changes carrying over to connecting roadways. The basic idea is that drivers adapt to higher speeds on the primary road and will be biased toward driving at those higher speeds once they switch to a connecting roadway. The evidence for carryover effects is limited, especially because many studies find such a small relationship between posted speed limit change and free-flow speed on the principal roads (*4*, *2*).

Another issue that may be worth examining in detail is the effects of speed limit changes on speed dispersion. Speed limit changes increase speed dispersion on interstate freeways, and variation in drivers' speed appears related to crash risk (*2*).

Cross References

Speeding Countermeasures: Setting Appropriate Speed Limits, 17-10
Speeding Countermeasures: Communicating Appropriate Speed Limits, 17-12
Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems, 17-14

Key References

1. Giles, M.J. (2004). Driver speed compliance in Western Australia: A multivariate analysis. *Transport Policy, 11*(3), 227-235.
2. Milliken, J.G., Council, F.M., Gainer, T.W., Garber, N.J., Gebbie, K.M., Hall, J.W., et al. (1998). *Special Report 254: Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits*. Washington, DC: Transportation Research Board.
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4. Parker, M.R., Jr. (1997). *Effects of Raising and Lowering Speed Limits on Selected Roadway Sections.* (FHWA-RD-92-084). McLean, VA: FHWA.
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SPEEDING COUNTERMEASURES: SETTING APPROPRIATE SPEED LIMITS

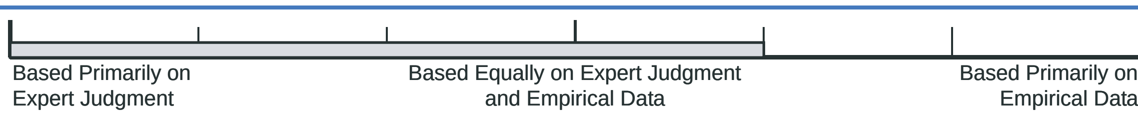
Introduction

Setting appropriate speed limits refers to guidelines and best practices for determining appropriate speed limits that take into account the unique traffic, design, and environmental aspects of the roadway. Much of the information in this guideline, as well as its companion guidelines ("Speeding Countermeasures: Communicating Appropriate Speed Limits" on page 17-12 and "Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems," on page 17-14), are adapted from Neuman et al. (*1*). As part of *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*, the study by Neuman et al. (*1*) was developed to address two key problems involved in excessive or inappropriate speeds: (1) driver behavior (i.e., deliberately driving at an inappropriate or unsafe speed) and (2) driver response to the roadway environment (i.e., inadvertently driving at an inappropriate or unsafe speed, failure to change speed in a proper or timely manner, or failure to perceive the speed environment). Both these problems result in an increased risk of a crash or conflict.

Design Guidelines

The design guidelines below should be used to help set appropriate speed limits. Additional guideline information is provided in the discussion section; however, the original source of these recommendations—Neuman et al. (*1*)—should be consulted for more specific design guidance.

Objective	General Strategy	Design Guideline
Set appropriate speed limits	Set speed limits that account for roadway design, as well as traffic and environmental conditions	Consider the: • **Design speed** of a major portion of the road, • **Vehicle operating speed**, measured as a range of 85th percentile speeds taken from spot speed surveys of free-flowing vehicles on the roadway, • **Safety experience** of the roadway, in the form of crash frequencies and outcomes, and • **Enforcement experience**; i.e., law enforcement's allowance for driving above the posted speed limit as well as the level of enforcement.
	Implement variable speed limits (VSLs)	While the efficacy of VSLs is uncertain (see also Milliken et al. (*2*)), they can be used for: • **Predictable events**, such as during school hours and construction activities, and • **Unpredictable events**, such as poor visibility due to fog or snow, and traffic incidents.
	Implement differential speed limits for heavy vehicles (high-speed areas only)	In high-speed areas, consider posting a lower speed limit for heavy trucks in order to reduce the severity of collisions involving trucks. *Note: Not all researchers agree that differential speed limits for trucks should be used, see the following discussion section.*



Discussion

As discussed in Neuman et al. (*1*), speed limits that appear inconsistent, fail to reflect the immediate roadway environment, or are inconsistent with driver expectancies may be ignored by drivers. This situation, in turn, can contribute to a lack of respect for and compliance with speed limits. The posted speed limit provides drivers with not just a legal limit, but also the maximum speed that highway engineers and road designers consider to be safe and appropriate. As noted by Milliken et al. (*2*), well-conceived speed limits also provide the basis for enforcement by law enforcement officers and the court system.

For the *set speed limits that account for roadway design, as well as traffic and environmental conditions* strategy, practicality and enforcement are key considerations. Setting the speed limit at the 85th percentile speed is expected to result in compliance by most drivers; however, unique design, traffic, or environmental characteristics of the roadway can also affect actual driving speeds. Such characteristics include proximity to schools or hospitals, an unusually high percentage of trucks in the traffic flow, unusually heavy pedestrian volumes, or a concentration of elderly pedestrians.

Variable speed limits (VSLs) are generally communicated through CMSs or other traffic control devices. A critical issue with VSLs is determining where they should be used, when the speed limits should be changed, and what the "other" speed limits should be; cameras or other detection equipment can be used to make these determinations (*1*). Visible and regular enforcement is also required to ensure compliance with the speed limits.

The use of *differential speed limits for heavy trucks* is an option for locations associated with a high incidence of truck crashes; however, the research is mixed with respect to the efficacy of doing so. The logic underlying the use of having a lower posted speed limit for trucks than for passenger vehicles is "that trucks have much longer stopping distances than do light vehicles and have other speed-related risks such as rollover at lower speeds and vulnerability to loss of control in cross winds" (*3*). The counterargument is that differential speed limits for trucks vs. cars increases the overall variability in vehicle speeds (at a given location at a given time), resulting in a greater potential for conflicts and crashes between trucks and cars. In a review of safety outcomes associated with heavy vehicles, Harwood, Potts, Torbic, and Glauz (*4*) found that the use of differential speed limits does not seem to reduce crashes, but may vary the distribution of crash types.

Design Issues

This guideline, and its companion guidelines ("Speeding Countermeasures: Communicating Appropriate Speed Limits" on page 17-12 and "Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems" on page 17-14), only include those countermeasures provided by Milliken et al. (*2*) that are directed at roadway design. Neuman et al. (*1*) should be consulted for a more detailed discussion of these countermeasures, as well as countermeasures intended (1) to heighten driver awareness of speeding-related safety issues and (2) to improve the efficiency and effectiveness of speed enforcement efforts.

Cross References

Speeding Countermeasures: Communicating Appropriate Speed Limits, 17-12
Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems, 17-14

Key References

1. Neuman, T.R., Slack, K.L., Hardy, K.K., Bond, V.L., Potts, I., and Lerner, N. (2009). *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 23: A Guide for Reducing Speeding-Related Crashes.* Washington, DC: Transportation Research Board.
2. Milliken, J.G., Council, F.M., Gainer, T.W., Garber, N.J., Gebbie, K.M., Hall, J.W., et al. (1998). *Special Report 254: Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits*. Washington, DC: Transportation Research Board.
3. Knipling, R.R., Waller, P., Peck, R.C., Pfefer, R., Neuman, T.R., Slack, K.L., et al. (2004). *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 13: A Guide for Reducing Collisions Involving Heavy Trucks.* Washington, DC: Transportation Research Board.
4. Harwood, D.W., Potts, I.B., Torbic, D.J., and Glauz, W.D. (2003). *CTBSSP Synthesis of Safety Practice 3: Highway/Heavy Vehicle Interaction*. Washington, DC: Transportation Research Board.

SPEEDING COUNTERMEASURES: COMMUNICATING APPROPRIATE SPEED LIMITS

Introduction

Communicating appropriate speed limits refers to guidelines and best practices for communicating posted speed limits to drivers. Much of the information in this guideline, as well as its companion guidelines ("Speeding Countermeasures: Setting Appropriate Speed Limits" on page 17-10 and "Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems" on page 17-14), are adapted from Neuman et al. (*1*). As part of *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*, the study by Neuman et al. (*1*) was developed to address two key problems involved in excessive or inappropriate speeds: (1) driver behavior (i.e., deliberately driving at an inappropriate or unsafe speed) and (2) driver response to the roadway environment (i.e., inadvertently driving at an inappropriate or unsafe speed, failure to change speed in a proper or timely manner, or failure to perceive the speed environment). Both these problems result in an increased risk of a crash or conflict.

Design Guidelines

The design guidelines below should be used to help communicate appropriate speed limits. Additional guideline information is provided in the discussion section; however, the original source of these recommendations—Neuman et al. (*1*)—should be consulted for more specific design guidance.

Objective	General Strategy	Design Guideline
Communicate appropriate speeds through the use of traffic control devices	Improve speed limit signage	• Locate speed limit signs where drivers expect them to be, such as following a major intersection. • Use advance notice signs (e.g., "Reduced Speed Ahead") to alert the driver to an upcoming speed change. • Consider context: where other traffic signs and/or commercial signs are abundant, use larger speed signs, increase the number of speed signs, or remove unnecessary signs.
	Implement active speed warning signs	• Use in locations where speeding has been observed or poses a safety risk, such as school zones, sharp horizontal curves, or locations with a history of speed-related crashes.
	Use in-pavement measures to communicate the need to reduce speeds	• May include transverse lines, peripheral transverse lines, chevron lines, and rumble strips.
	Implement changeable message signs (high-speed areas only)	• Use CMSs to present information relevant to traffic conditions, work zones, weather and road surface conditions, detour/directional information, crashes and incidents, and appropriate speed limits.

Discussion

As discussed in Neuman et al. (*1*), information about speed limits—in the form of signs or markers—should be clearly communicated to drivers, at appropriate locations on the roadway. The posted speed limit provides drivers with not just a legal limit, but also the maximum speed that highway engineers and road designers consider to be safe and appropriate. The placement and visibility of speed signs are key to properly communicating speed limits.

Improving speed limit signage is especially important in areas where signs are frequently obscured by other signage, vegetation, or adverse weather conditions. Also, having a high percentage of older drivers on a particular section of the roadway is often a good reason to address signage location and visibility. Providing conspicuous and redundant information about unexpected posted speed changes, such as those greater than 10 mi/h, can also increase driver awareness of a speed change. This information can be provided by using "Speed Reduction Ahead" signs in advance of the change, placing signs on both sides of the roadway, and using signs with salient features (e.g., fluorescent flags) (*1*). Additional supplementary signs spaced every 60 s of travel (or more frequently in urban areas with increased access to the road) can also promote driver awareness of the speed limit.

Active speed warning signs improve drivers' awareness of both their current speed and the posted speed limit in order to deter speeding behaviors. In Bloch (*2*), a before–after evaluation was conducted to assess the benefits of using a speed warning sign. The study found that mean speed was reduced at the sign location, but that intermittent enforcement was required to significantly reduce speeds downstream from the sign. The sign was effective in reducing excessive speeds (i.e., speeds 10 mi/h above the posted speed).

In-pavement measures and other perceptual measures can be used to encourage drivers to adhere to speed limits (*1*). Pavement marking—such as transverse lines, peripheral transverse lines, and chevron lines—gives the illusion that the driver is driving faster than his/her actual speed and can be used as a means to decrease excessive speeds by reducing the driver's comfort level at higher speeds (*1*). These approaches can be used along any roadway segment where speed may be a problem, as well as locations where speed reductions are necessary, such as intersection approaches, work zones, toll plazas, and ramps. Rumble strips (e.g., continuous shoulder rumble strips, centerline rumble strips, or transverse rumble strips) may also be used to reduce vehicle speeds or to prevent crashes where speed is a causal factor (*1*). In this role, rumble strips are used as a traffic calming device in, for example, high-pedestrian areas such as parks, schools, hospitals, and residential areas. Rumble strips are also discussed in "Shoulder Rumble Strips" on page 16-6.

CMSs can also be used to display information on appropriate speeds relative to current conditions. See Chapter 19 for more details on when and how to use CMSs.

Design Issues

This guideline, and its companion guidelines ("Speeding Countermeasures: Setting Appropriate Speed Limits" on page 17-10 and "Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems," on page 17-14), only include those countermeasures provided by Milliken et al. (*3*) that are directed at roadway design. Neuman et al. (*1*) should be consulted for a more detailed discussion of these countermeasures, as well as countermeasures intended (1) to heighten driver awareness of speeding-related safety issues and (2) to improve the efficiency and effectiveness of speed enforcement efforts.

Cross References

Speeding Countermeasures: Setting Appropriate Speed Limits, 17-10
Speeding Countermeasures: Using Roadway Design and Traffic Control Elements to Address Speeding Problems, 17-14
Rumble Strips, 16-6

Key References

1. Neuman, T.R., Slack, K.L., Hardy, K.K., Bond, V.L., Potts, I., and Lerner, N. (2009). *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 23: A Guide for Reducing Speeding-Related Crashes.* Washington, DC: Transportation Research Board.
2. Bloch, S.A. (1998). A comparative study of the speed reduction effects of photo-radar and speed display boards. *Transportation Research Record, 1640,* 27–36.
3. Milliken, J.G., Council, F.M., Gainer, T.W., Garber, N.J., Gebbie, K.M., Hall, J.W., et al. (1998). *Special Report 254: Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits.* Washington, DC: Transportation Research Board.

SPEEDING COUNTERMEASURES: USING ROADWAY DESIGN AND TRAFFIC CONTROL ELEMENTS TO ADDRESS SPEEDING PROBLEMS

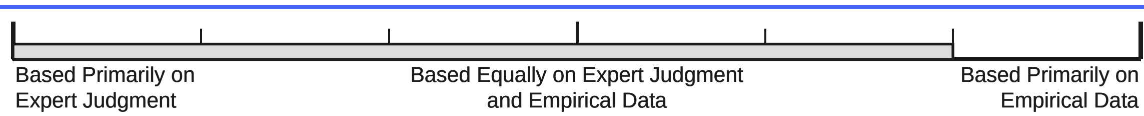
Introduction

Using roadway design and traffic control elements to address speeding problems refers to guidelines and best practices for selecting and using geometric design features and traffic signals to support safe speed decisions by drivers. Much of the information in this guideline, as well as its companion guidelines (*Speeding Countermeasures: Setting Appropriate Speed Limits* on page 17-10 and *Speeding Countermeasures: Communicating Appropriate Speed Limits* on page 17-12), is adapted from Neuman et al. (*1*). As part of *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*, the study by Neuman et al. (*1*) was developed to address two key problems involved in excessive or inappropriate speeds: (1) driver behavior (i.e., deliberately driving at an inappropriate or unsafe speed) and (2) driver response to the roadway environment (i.e., inadvertently driving at an inappropriate or unsafe speed, failure to change speed in a proper or timely manner, or failure to perceive the speed environment). Both these problems result in an increased risk of a crash or conflict.

Design Guidelines

The design guidelines below should be used to select and use geometric design features and traffic signals to support safe speed decisions by drivers. Additional guideline information is provided in the discussion section; however, the original source of these recommendations—Neuman et al. (*1*)—should be consulted for more specific design guidance.

Objective	General Strategy	Design Guideline
Ensure that roadway design and traffic control elements support appropriate and safe speeds	Use consistent combinations of geometric elements to control speeds.	• Design features such as curve radius, tangent length, length of spirals, vertical grades and curves, available sight distance, and cross-section features should be designed consistently across locations, in a manner that meets driver expectancies.
	Provide adequate change + clearance intervals at signalized intersections.	• Clearance intervals should account for expected approach speeds and should reflect operating speeds, intersection width, vehicle lengths, and driver characteristics such as reaction time and braking. See Tutorial 4 for the equation developed by ITE (*2*) for determining clearance intervals.
	Provide protected left turns.	• Implement protected-only signal phasing for left turns at high-speed signalized intersections.
	Provide improved visibility.	• Install lighting at high-speed sections of the roadway, especially intersections.



Discussion

As discussed in Neuman et al. (*1*), while drivers ultimately select their own speeds, they receive, process, and use a number of cues from the immediate driving environment when doing so. Key elements of the driving environment that can effectively communicate safe speeds are roadway design and the use and operation of traffic control devices.

Design consistency is a key principle in roadway design. Using *consistent combinations of geometric elements* leads to roadway elements that meet driver expectancies and can result in consistent speeds and fewer unexpected speed changes. For example, large differences and sudden changes in horizontal alignment, available sight distance, curve radii, etc. should be avoided, as these can increase driver workload, misperceptions, errors, and—ultimately—the likelihood of crashes.

Clearance intervals provide safe transitions in right-of-way (ROW) assignment between crossing or conflicting flows of traffic. One way to accomplish safe transitions is an all-red interval, which should be designed to account for expected approach speeds to reduce the likelihood of collisions resulting from red light running. Clearance intervals that are too short can result in drivers not being able to stop in time for the red light; drivers can also stop too quickly, increasing the risk of rear-end collisions from following vehicles. Clearance intervals that are too long can lead to driver impatience, or red light running, especially in drivers familiar with the intersection. Whether the concern is red light running or increased risk of collisions, both outcomes are exacerbated by speeding.

On high-speed roadways, especially in high traffic volume situations, there may be inadequate gaps for left-turning vehicles. *Protected-only left-turn signals* have a phase designated specifically for left-turning vehicles. Other factors that may warrant the use of protected-only left-turn phases include delay, visibility, distance of the intersection, and safety at the intersection (e.g., crash history) (*1*). The benefits of protected-only left turns include increasing left-turn capacity and reducing intersection delays for vehicles turning left (*3*). The use of protected left-turn phases also improves safety by removing conflicts during a left-turn movement. This improved safety can be especially important on roadways where high operating speeds can contribute to the crash severity and may play a role in the difficulty a driver has with identifying and selecting a safe gap (*1*). However, the use of protected-only left-turn signals will usually increase the cycle length, which also increases delay. For additional discussion and guidance on the type of left-turn phase to use in a given situation, see Pline (*4*).

On high-speed roads, drivers have less time to detect visual information because vehicles are traveling faster. This problem is compounded at night when the visual contrast of some roadway elements is reduced and drivers require more time to detect visual information (drivers at higher speeds will also travel farther during this elongated detection period and consequently have less time to react to hazards). While increasing *lighting* on its own will not prevent speeding, it will make potential hazards or other important information easier for drivers to see, particularly during nighttime and adverse weather conditions.

Design Issue

This guideline, and its companion guidelines ("Speeding Countermeasures: Setting Appropriate Speed Limits" and "Speeding Countermeasures: Communicating Appropriate Speed Limits"), only include those countermeasures provided by ITE (*2*) that are directed at roadway design. Neuman et al. (*1*) should be consulted for a more detailed discussion of these countermeasures, as well as countermeasures intended (1) to heighten driver awareness of speeding-related safety issues and (2) to improve the efficiency and effectiveness of speed enforcement efforts.

Cross References

Speeding Countermeasures: Setting Appropriate Speed Limits, 17-10
Speeding Countermeasures: Communicating Appropriate Speed Limits, 17-12
Design Consistency in Rural Driving, 16-8

Key References

1. Neuman, T.R., Slack, K.L., Hardy, K.K., Bond, V.L., Potts, I., and Lerner, N. (2009). *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 23: A Guide for Reducing Speeding-Related Crashes.* Washington, DC: Transportation Research Board.
2. ITE (1994). *Determining Vehicle Signal Change and Clearance Intervals.* Washington, DC.
3. Brehmer, C.L., Kacir, K.C., Noyce, D.A., and Manser, M.P. (2003). *NCHRP Report 493: Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control.* Washington, DC: Transportation Research Board.
4. Pline, J.L. (1996). *NCHRP Synthesis of Highway Practice 225: Left-Turn Treatments at Intersections*. Washington, DC: Transportation Research Board.

PART IV

Human Factors Guidance for Traffic Engineering Elements

CHAPTER 18

Signing

GENERAL PRINCIPLES FOR SIGN LEGENDS

Introduction

Sign legends refer to the text and/or symbols composing the sign message. Legends that are too long or too complicated can lead to problems in comprehension. In general, the legend on a sign must be kept to a minimum, regardless of letter size, to maximize driver comprehension.

Design Guidelines

Type of Sign	Example (all from MUTCD (1))	Guidelines
Advance Guide		• Limit route and destination information to a total of three lines • Do not use more than two destination/street names. • Place intersecting streets on top line and distance to intersecting streets on bottom.
Conventional Guide		• Limit route and destination information to a total of three lines.
Exit Direction		• Limit route and destination information to a total of three lines. • Do not include more than two destination/street names.
Tourist		• Place symbols to the left of the word legend. • Limit information to a total of two lines.
Service		• Limit general road user services to six.
Distance		• Limit traffic generators to three accompanied by the related distance. • Keep the highest priority distance (nearest distance) at the top or left.
Lane Control		• Place the legend at the top of the sign.

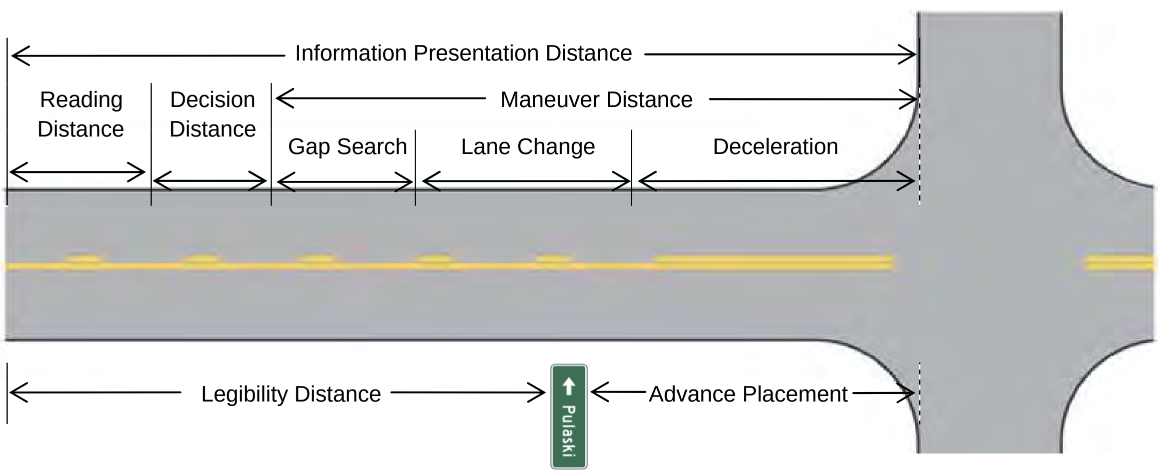
Discussion

The relatively small amount of available space on roadway signs suggests the need to make the best use of this space when designing legends. The guidelines on the previous page have been adapted from the MUTCD (*1*) because of their common focus on legends and because they are provided across various sections/pages within the MUTCD and can be hard to find. In general, they reflect acceptable, best practices for sign legends. The legend for a sign should be selected to maximize information transmission and comprehension, given both the nature of the sign's message and general roadway environment. Text-based signs are clearly more appropriate than symbolic signs for highly complex messages, such as destination messages or hazards that are more quickly and easily presented via text rather than potentially ambiguous or unfamiliar symbols.

There is a trade-off between the amount of information provided in a sign, the complexity of the sign information, and its overall comprehensibility. Either through the use of more words or through the use of complex graphics, the density of information presented on a sign can be increased, but often at the cost of legibility and/or comprehensibility. New sign designs (or even existing signs being used in a new location or a new way) should always be tested, using a representative group of drivers, to see if they support adequate levels of driver comprehension.

Design Issues

Sign placement and appropriate letter height are determined by a number of factors. A process for determining these values is presented in the *Traffic Control Devices Handbook* (*2*) and discussed in more detail in Tutorial 5. Appropriate sign placement is determined by the overall *information presentation distance,* which is the total distance at which the driver needs information about the choice point (e.g., intersection). This distance is the sum of the reading distance, the decision distance, and the maneuver distance. The reading distance is determined by the amount of time that the driver needs to read the sign's message, depending on the number of words, numbers, and symbols contained in the message. The decision distance is determined by the amount of time needed to make a choice decision and initiate a maneuver. The decision time necessary depends on the complexity of the maneuver. The maneuver distance is determined by the time necessary to complete any maneuver required by the choice. For a lane change maneuver, this distance is the sum of the gap search, lane change, and deceleration distances. These values are all influenced by the vehicle operating speed. Once the reading, decision, and maneuver distances are summed to find the information presentation distance, the advance placement distance between the sign and the choice point can be subtracted to find the *legibility distance*, which is the distance at which the sign must be legible. The required letter height can be calculated by referencing the legibility index provided in the MUTCD (30 ft/in.). When the legibility distance is divided by the legibility index, the letter height is obtained.



Cross References

Presentation to Maximize Visibility and Legibility, 19-4
Sight Distance Guidelines, 5-1

Key References

1. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
2. Pline, J.L. (Ed.). (2001). *Traffic Control Devices Handbook.* Washington, DC: ITE.

SIGN DESIGN TO IMPROVE LEGIBILITY

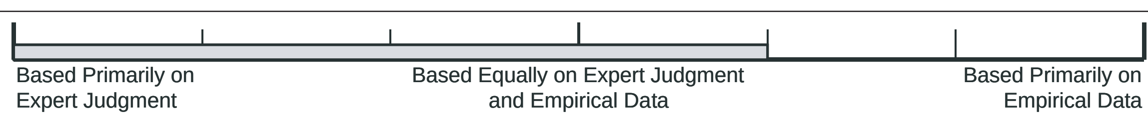
Introduction

Sign design refers to the design parameters of signs that impact the legibility of text placed on the sign. Sign legibility is greatly affected by specific design characteristics of signs that contribute to drivers' ability to perceive and understand a sign's message in order to promote safe driving behaviors. Key design parameters determining the legibility of signs include retroreflectivity (sheeting type) and legend color, font size, and font style.

Design Guidelines

The following guidelines can be used to improve sign legibility.

Sign Design Characteristics	Guidelines
Retroreflective (Sheeting Type)	• Microprismatic retroreflective sheeting provides longer legibility distances than encapsulated retroreflective sheeting by 9.5% (*1*).
Legend Color	• Light letters on a dark background are superior to dark letters on a light background (*2*). • Black-on-orange and white-on-green signs are detected at greater distances than black-on-white signs (*3*).
Font Size	• A maximum legibility index of 40 ft/in. of letter height should be used (*4*). • Research indicates that legibility distance increases as letter height increases, although the benefits are not proportional above letter heights of about 8 in. (*3*).
Font Style	• Legibility of overhead guide signs and shoulder-mounted guide signs is increased with microprismatic sheeting with Clearview™ alphabet over Series E (modified) (*5*). • Increased legibility distance is found with mixed-case text under daytime and nighttime conditions (*3*).
Symbol Contrast	• Optimal legend to background contrast value for sign legibility is 12:1 (*3*). • Positive-contrast signs provide greater legibility distances than negative-contrast signs (*3*).
General Improvements for Older Drivers (all from FHWA (*6*))	• Minimize symbol complexity by using very few details. • Maximize the distance between symbol sign elements. • Use representational rather than abstract symbols (see also Campbell, Richman, Carney, & Lee (*7*)). • Use solid rather than outline figures for design. • Standardize the design of arrowheads, human figures, and vehicles. • Retain maximum contrast between the symbol and the sign background. • Use a larger font when possible.



Discussion

The table on the previous page summarizes key design guidelines that can help improve sign legibility and safety. A great number of studies have examined specific properties of roadway signs that affect legibility, and many of the results from these studies are reflected in the MUTCD. Garvey, Thompson-Kuhn, and Pietrucha (*3*) contributed a number of the guidelines on the previous page; this data source was a comprehensive review and synthesis of existing research associated with the use and design of roadway signs.

Design Issues

Drivers cannot see as well under nighttime conditions as they can under normal daytime conditions. Additional factors that compromise vision at night, consequently affecting legibility distances, are summarized in the following table.

Factors that Compromise Vision at Night	
Glare	Glare from headlights, overhead signs, and construction lights can cause problems for approaching drivers. Drivers traveling in the same direction may experience glare issues when lights shine in their rearview mirrors.
Fatigue/Lack of Alertness	Fatigue and lack of alertness problems increase at night. The degree of these problems may be more apparent as drive time increases.
Poor Lighting	When driving during the daytime there is usually enough light to see well. This is not true at night. Even with the presence of lights, the road scene may still be confusing as signs may be hard to see amongst other signs, shop windows, and other lights.
Headlights	Headlights provide the main source of light for drivers to see and be seen under nighttime conditions. Drivers cannot see as far or see as much detail with headlights as compared to daytime driving conditions. Also, drivers tend to overdrive their headlights under certain conditions at night. Typically, the maximum distance for which modern headlamps provide reasonable illumination is between 150 and 250 ft, depending on headlamp characteristics and the reflectivity of the object being seen (*8*). In urban/suburban areas, drivers normally dim their headlights, which reduces visibility distance. Prismatic grade sign sheeting helps improve driver visibility in these areas.
Windshield and Mirrors	Bright lights at night can cause dirt on windshields or mirrors to create glare.

Cross References

Driver Comprehension of Signs, 18-8

Key References

1. Carlson, P.J., and Hawkins, G. (2003). Legibility of overhead guide signs with encapsulated versus microprismatic retroreflective sheeting. *Transportation Research Record, 1844*, 59-66.
2. Sivak, M., and Olson, P.L. (1983). *Optimal and Replacement Luminances of Traffic Signs: A Review of Applied Legibility Research.* (UMTRI-83-43). Ann Arbor: University of Michigan Transportation Research Institute.
3. Garvey, P.M., Thompson-Kuhn, B., and Pietrucha, M.T. (1996). *Sign Visibility: Research and Traffic Safety Overview.* Bristol, PA: United States Sign Council.
4. Chrysler, S.T., Carlson, P.J., and Hawkins, H.G. (2002). *Nighttime Legibility of Ground-Mounted Traffic Signs as a Function of Font, Color, and Retroreflective Sheeting Type.* (FHWA/TX-03/1796-2, TTI: 0-1796). College Station: Texas Transportation Institute.
5. Hawkins, H.G., Jr., Picha, D.L., Wooldridge, M.D., Greene, F.K., and Brinkmeyer, G. (1999). Performance comparison of three freeway guide sign alphabets. *Transportation Research Record, 1692*, 9-16.
6. FHWA (1995). *Improvements in Symbol Sign Design to Aid Older Drivers. Summary Report*. (FHWA-RD-95-129). McLean, VA.
7. Campbell, J.L., Richman, J.B., Carney, C., and Lee, J.D. (2004). *In-Vehicle Display Icons and Other Information Elements. Volume I: Guidelines* (FHWA-RD-03-065). McLean, VA: FHWA. (http://www.tfhrc.gov/safety/pubs/03065/index.htm).
8. Schiller, C., Holger, S., Groh, A., Böll, M., and Khanh, T.Q. (2009). *HID vs. Tungsten Halogen Headlamps: Driver Preferences and Visibility Distance*. (2009-01-0550). Warrendale, PA: Society of Automotive Engineering.

CONSPICUITY OF DIAMOND WARNING SIGNS UNDER NIGHTTIME CONDITIONS

Introduction

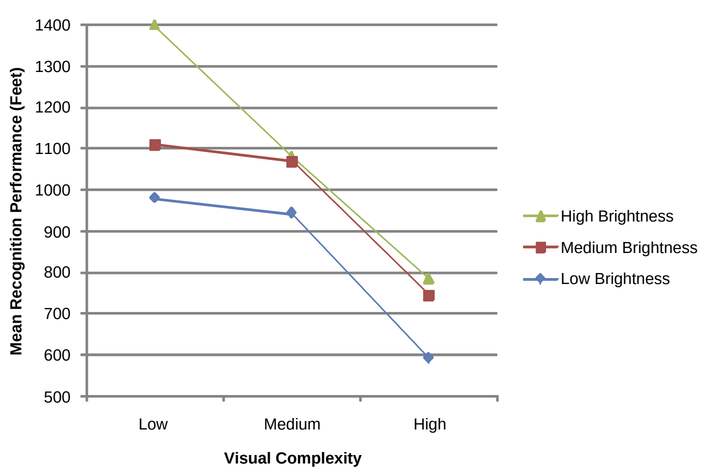
Conspicuity refers to how easy it is to see and locate a visual target. In the context of road signs, it represents how easy it is to distinguish a sign from the surrounding visual environment. Visual conspicuity is particularly important when providing important information because drivers are typically reluctant to spend more than 2 s with their eyes off of the roadway. Consequently, the easier drivers can find a sign, the more time they have to comprehend the sign information. Also, at a more basic level, increasing the conspicuity of a sign will reduce the chance that drivers will miss or be unable to read the sign information altogether. Nighttime visibility is a special problem for sign design, as reduced illuminance (relative to daytime conditions) is associated with reduced target contrast and generally reduced visibility for drivers. Related to traffic control devices in general, the MUTCD (*1*) provides design considerations that specify that "devices should be designed so that features such as size, shape, color, composition, lighting or retroreflection, and contrast are combined to draw attention to the devices." As discussed in more detail below, a critical factor in facilitating the driver's ability to find and comprehend warning signs at night is to maximize the sign's visual conspicuity relative to surrounding background elements. The figure below illustrates the relationship between sign recognition by drivers, sign brightness, and the complexity of the sign's immediate environment.

Design Guidelines

Sign Characteristics	Environment Characteristics
• Increase sign brightness relative to its surround. • Increase brightness contrast between different parts/elements of the sign. • Increase the sign's size relative to other objects in the visual field/environment. • Use a sign hue that contrasts with other noise/background items.	• Reduce the number and density of background noise items, especially those immediately adjacent to the sign. • Increase the distance between the sign and noise items.

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

RECOGNITION PERFORMANCE BY VISUAL COMPLEXITY AND SIGN BRIGHTNESS



Source: adapted from Mace, King, and Dauber (*2*)

Discussion

Mace et al. (*2*) describe a study conducted to establish luminance levels for conspicuity of yellow diamond warning signs at night. A key finding of the study was that, while many factors influence the visibility of a road sign, the visual complexity of a scene is most important in determining nighttime sign luminance requirements. Specifically, the complexity of the area immediately surrounding a sign (e.g., other signs, lights, structures, trees, etc.) greatly influences a driver's ability to perceive and extract information from a sign.

When sites are assessed or classified on their visual complexity, the following factors are rated:

- The amount of detail visible in the visual scene, quantified as the number of objects or percentage of the scene with visible detail
- The number of bright light sources—streetlights, signs, cars, billboards, store windows, reflection, etc.—located in the scene
- The amount of visible detail contained in the *cone* (that portion on the right-hand side of the roadway where a driver would typically look for road signs) of the scene
- The visual demands associated with the portion of the roadway associated with the sign (i.e., the percentage of the driver's time that would be spent looking for driving-relevant information while at that location)

A broader summary of relevant research provided in Mace et al. (*2*) concluded that the attention-getting value of a target increases as (1) the target's brightness increases, (2) the brightness contrast between the target and its surround increases, (3) the brightness contrast between different parts of the target increases, (4) the target's size increases relative to other stimuli in the visual field, (5) the shape of the target contrasts with noise items, (6) the target's hue contrasts with noise, (7) the number of noise elements in the visual field decreases, (8) the overall density of noise items in the visual field decreases, (9) the density of noise items immediately adjacent to the target decreases, (10) the distance between the target and noise increases, (11) the number of irrelevant classes of stimuli in the visual field decreases, and (12) the variability within each irrelevant class of stimuli decreases. Although sign conspicuity is clearly important, compliance with the specifications set by the MUTCD for sign shape and other characteristics is essential.

Design Issues

A key factor to consider in improving the conspicuity and visibility of highway signs is the importance of individual differences across the driver population. In particular, older drivers have poorer rates of detection and recall of signs than do younger drivers (*3*), and slower response times (*4*). Thus, conspicuity and visibility for older drivers should be a key concern in the design and placement of signs.

Another factor in driver reaction to signs is their relevance to the drivers at a particular time and place. A series of studies have demonstrated that the greater the relevance to a particular trip and the greater their need for the information provided by the sign, the more likely that drivers will pay attention to the sign (*5*).

Cross References

Presentation to Maximize Visibility and Legibility, 19-4

Key References

1. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
2. Mace, D.J., King, R.B., and Dauber, G.W. (1985). *Sign Luminance Requirements for Various Background Complexities* (FHWA-RD-85-056). McLean, VA: FHWA.
3. Al-Gadhi, S.A., Naqvi, S.A., and Abdul-Jabbar, A.S. (1994). Driver factors affecting traffic sign detection and recall. *Transportation Research Record, 1464*, 36-41.
4. Garvey, P.M., and Kuhn, B.T. (2004). Highway sign visibility. In *Handbook of Transportation Engineering.* (Chapter 11). New York: McGraw-Hill.
5. MacDonald, W.A., and Hoffmann, E.R. (1984). *Drivers' Awareness of Traffic Sign Information.* (AIR 382-1). Vermont South, Victoria: Australian Road Research Board.

DRIVER COMPREHENSION OF SIGNS

Introduction

Sign comprehension refers to a driver's or road user's ability to interpret the meaning of a sign. Signs should be designed and presented so that their message is comprehended and understood by users. As discussed in Campbell, Richman, Carney, and Lee (*1*), in the context of icons and symbols, there are three stages associated with the comprehension and use of signs: legibility, recognition, and interpretation. Legibility reflects the relationships among the driver, the sign, and the environment; it is essential for the initial perception of the sign and includes parameters such as luminance uniformity, contrast, and size. Recognition reflects whether or not the driver can readily distinguish the sign, especially in the context of other signs and stimuli. Interpretation reflects the relationships among the driver, the sign, and the referent or message associated with the sign; it includes parameters such as whether the driver comprehends the meaning, intent, or purpose of the sign. This guideline identifies message format recommendations for improving drivers' comprehension of road signs. As shown below, information can be presented in a text-only, graphic/icon-only, or mixed text–graphic format.

Design Guidelines

The following guidelines provide parameters for the use of text-only, graphic/icon-only, or mixed text–graphic formats.

Format	Example	Guidelines
Text Only		• Use for highly complex messages. • Use when indicating hazards. • Use for destination information. • Use in areas requiring unexpected or unique driver actions, e.g., frequent lane shifts.
Graphic / Icon Only		• Use for safety and warning information. • Use for prohibited actions. • Use in visually degraded conditions. • Use in areas with higher posted speeds. • Use diagrammatic graphics when road geometry violates driver expectancies. • Minimize symbol complexity by using few details.
Mixed		• Add text when symbols alone are unintuitive. • Keep text to no more than two to three words. • Use a clear and simple font for the text.

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Discussion

The figure below shows the three stages that appear to be associated with comprehension and use of signs: legibility, recognition, and interpretation. As shown below, this sequence of icon comprehension refers to the perceptual and cognitive process by which users interpret the meaning of a sign.

Legibility → **Recognition** → **Interpretation**

Legibility
- Can the driver see the sign?
- Is it legible at various distances?
- Can it be seen under both nighttime and daytime lighting conditions?

Recognition
- How well do the parts of this sign relate to one another?
- Does the construction of the sign support accurate recognition?
- Is it easily confused with other signs?

Interpretation
- How well does the sign convey the message?
- Will it be understood when presented in the appropriate context?
- Does it require special knowledge particular to a culture, language, or driver age?

Source: adapted from Campbell et al. (*1*)

The format of a sign—i.e., text only, graphic/icon only, or mixed—should be selected to maximize information transmission and comprehension, given the nature of both the sign's message and the general roadway environment. Text-based signs are clearly more appropriate for highly complex messages, such as destination messages or hazard warnings that are more quickly and easily presented via text. It has long been recognized that well-designed icons are generally recognized more accurately and quickly than text-based signs meant to convey the same message (*2*) and that icons can be presented in a much more spatially condensed form (*3*, *4*, *5*) than can most text-based messages. Road signs also have a limited amount of space for presenting information and must take advantage of the ability of icons to present more information to the driver than can be presented textually. Research in this domain has shown that icons can be recognized more rapidly and are legible at greater distances than information presented in other formats (*6*, *7*). The absolute numerical differences in mean reaction times are not relevant because of the differences between the task performed in the study and the actual driving task.

Design Issues

Comprehension tests are evaluation techniques that provide a means to determine whether a candidate sign for a roadway message is likely to be properly understood by typical roadway users. Overall, a rigorous and iterative evaluation process will increase the likelihood that the implementation of the sign on the roadway will improve overall traffic safety, and not detract from it. A number of procedures can be used to measure driver comprehension of signs, including the recently released J2830, *Process for Comprehension Testing of In-Vehicle Icons*, an SAE Information Report within the SAE Standards series.

Also, road engineers may consider message format based on location and driver demographics. For example, non-native-English speakers can correctly interpret graphic messages without relying on their knowledge of the English language. An increased use of transportation graphic signs in the vicinity of non-native-English-speaking population areas may be appropriate.

Cross References

Presentation to Maximize Visibility and Legibility, 19-4

Key References

1. Campbell, J.L., Richman, J.B., Carney, C., and Lee, J.D. (2004). *In-Vehicle Display Icons and Other Information Elements. Volume I: Guidelines* (FHWA-RD-03-065). McLean, VA: FHWA (http://www.tfhrc.gov/safety/pubs/03065/index.htm).
2. Edworthy, J., and Adams, A. (1996). *Warning Design: A Research Prospective*. Bristol, PA: Taylor & Francis.
3. Zwaga, H.J., and Boersema, T. (1983). Evaluation of a set of graphic symbols. *Applied Ergonomics, 14*, 43-54.
4. Rohr, G., and Keppel, E. (1984). *Iconic Interfaces: Where to Use and How to Construct Human Factors in Organisational Design and Management*. The Netherlands: North-Holland.
5. Hemenway, K. (1982). Psychological issues in the use of icons in command menus. *Proceedings of the CHI 1982 Conference on Human Factors in Computer Science* (pp. 20-23). New York: Association for Computing Machinery.
6. Ells, J.G., and Dewar, R.E. (1979). Rapid comprehension of verbal and symbolic traffic sign messages. *Human Factors, 21*, 161-168.
7. Jacobs, R.J., Johnston, A.W., and Cole, B.L. (1975). The visibility of alphabetic and symbolic traffic signs. *Australian Road Research, 5*(7), 68-86.

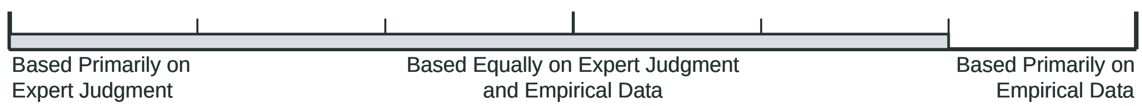
COMPLEXITY OF SIGN INFORMATION

Introduction

The *complexity of sign information* refers to the number of information units presented as part of a roadway sign message. In this context, an information unit can describe geography (e.g., city), type of roadway (e.g., highway), event causes (e.g., stalled vehicle), event consequences (e.g., traffic jam), time and distances, and proposed actions. Therefore, information units can be described as the relevant words in a message. Much of the guideline information presented below has been adapted from Campbell, Carney, and Kantowitz (*1*).

Design Guidelines

- Messages that require an urgent action should be a single word or a short sentence with the fewest number of syllables possible. Drivers should be able to understand the message immediately.
- Messages that are not urgent or for which a response may be delayed can be a maximum of 7 units of information in the fewest number of words possible. If the information cannot be presented in a short sentence, the most important information should be presented at the beginning and/or the end of the message.
- Navigation instructions should be limited to 3 or 4 information units.



DETERMINING THE NUMBER OF INFORMATION UNITS

4 units	Road Construction Ahead at Jaspertown
8 units	Road Construction on Interstate 5 for next 10 miles Take Highway 99
11 units	Interstate 80 closed for construction between Iowa City and Cedar Rapids Exit at West Liberty and drive north on Highway 16
16 units	Accident Ahead Exit 215 closed to Dover Traffic detoured to Exit 216 Follow Highway 46 to Chester and turn east onto Inglenook Road

EFFECTS OF INFORMATION COMPLEXITY

	Length of Message			
	3-4 units	**6-8 units**	**10-12 units**	**14-18 units**
Duration of Each Glance	1.08 s	1.18 s	1.20 s	1.35 s
Number of Glances	3.8	6.9	9.6	15.5
Memory Recall	100%	97.5%	75.4%	52.4%

Source: Labiale (*2*)

Discussion

The longer the message, the more processing time the driver requires. Therefore, messages that require the driver to make an immediate response should be as short as possible. One-word messages informing the driver of the appropriate action to take might work best in these situations. As the response required by the driver becomes less and less urgent, the messages can become more detailed; however, an effort should still be made to make the messages as concise as possible.

Zwahlen, Adams, and DeBald (*3*) analyzed the number of lane deviations that occurred while drivers were operating a CRT touch screen. The results suggest that the number of glances away from the roadway should be limited to three and that glance durations that exceeded 2 s in duration are unacceptable. Zwahlen et al. (*3*) examined the amount/complexity of information necessary for evoking these unsafe glance frequencies and durations. The results of this on-road study suggest that although the duration of glances does not increase dramatically as the number of information units increase, the number of glances does. Therefore, the shortest information message (3 to 4 units) would be the most appropriate for keeping drivers' attention on the forward roadway. The driver's ability to recall information was also examined in Labiale (*2*): only 75% of a 10- to 12-unit message could be recalled, in comparison to 100% of a 3- to 4-unit message and 98% of a 6- to 8-unit message. This finding is consistent with Miller (*4*), which proposed that the maximum capacity of working memory is "seven, plus or minus two" chunks of information. Again, this finding suggests that keeping the message short, 3 to 8 information units, would increase the likelihood that it will be recalled by the driver.

Design Issues

Complexity is a function of how much information is being provided and how difficult it is to process. The phrase "information units" is used to describe the amount of information presented, in terms of key nouns and adjectives contained within a message.

High-Complexity Examples	Low-Complexity Examples
> 9 information units	3-5 information units
Processing time > 5 s	Processing time < 5 s
Examples: Topographical representations of a route, or full route maps, or schedules for alternative modes of transportation.	Examples: Directions of turns, or estimates of travel costs.

Cross References

Driver Comprehension of Signs, 18-8

Key References

1. Campbell, J.L., Carney, C., and Kantowitz, B.H. (1998). *Human Factors Design Guidelines for Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO)* (FHWA-RD-98-057). Washington, DC: FHWA.
2. Labiale, G. (1996). Complexity of in-car visual messages and driver's performance. In A.G. Gale et al. (Eds.). *Vision in Vehicles, 5* (pp. 187-194). Bron Cedex, France: INRETS.
3. Zwhalen, H.T., Adams, C.C., Jr., and DeBald, D.P. (1988). Safety aspects of CRT touch panel controls in automobiles. In A.G. Gale et al. (Eds.). *Vision in Vehicles, 2* (pp. 335-344). Amsterdam: Elsevier Science.
4. Miller, G.A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*, 81-97.

CHAPTER 19

Changeable Message Signs

WHEN TO USE CHANGEABLE MESSAGE SIGNS

Introduction

When to use changeable message signs refers to the general principles regarding the appropriate display of traveler information messages on CMSs. These signs can be used to effectively manage travel, control traffic, identify current and anticipated roadway conditions, and regulate access (*1*). However, inappropriate application and use can reduce the effectiveness of these signs. Note that the terms “changeable message sign” (CMS), “dynamic message sign” (DMS), and “variable message sign” (VMS) are used interchangeably in the literature to refer to these signs. Because there is no functional distinction between the terms, “changeable message sign” or “CMS” is used throughout this chapter to refer to CMSs, DMSs, and VMSs.

Design Guidelines

The following guidelines can be used to improve the effectiveness of displaying traveler information with CMSs.

When to Use CMSs	Examples (adapted from Dudek (*4*))
• To display essential information about: – Random unpredictable incidents such as crashes – Temporary, pre-planned activities such as construction – Environmental problems such as snow – Special event traffic such as for parades – Special operational problems such as reversible lanes – Recurrent problems such as travel times due to congestion – AMBER alerts or emergency security incidents	
• To display messages for less than 2 weeks.	
• In conjunction with other media (e.g., Highway Advisory Radio) if conveying extensive or complex messages.	
• To display up-to-date, real-time information that is accurate and credible.	

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

Discussion

CMSs are an essential part of the driver information system. They are an important link between transportation agencies and the driving public. They allow for the display of time-sensitive or temporary information that affects travel and in many cases requires drivers to take an action (*1*). It is important that drivers find these messages to be relevant so that they will continue to pay attention to the signs. A field study analyzed by Richards and Dudek (*2*) showed that CMSs that are operated for long periods with the same message may lose their effectiveness. If drivers begin ignoring a sign, they may not notice or may ignore important roadway information when it is available (*3*). Johnson (*1*) also states that drivers tend to ignore messages that are displayed for long periods of time and recommends that safety campaign messages be limited to a few weeks.

The content displayed on CMSs is limited by the amount of time that the driver has to read the display. This time is affected by both the legibility distance of the sign and the speed of travel. The legibility distance is influenced by a number of factors including weather conditions (e.g., rain, fog), geography (e.g., hills), and roadway conditions (e.g., the presence of large trucks) (*4*). CMS reading times are higher than those for static signs because drivers can scan static signs for essential information whereas they must read the entire CMS to understand its message. Static signs also have the advantages of being seen daily and of being uniformly formatted. At highway speeds, the CMS message must be readable in 8 s or less (*4*). Displaying messages that are longer than this limit can affect traffic flow and sign credibility. Thus, it is recommended that extensive messages be displayed in conjunction with other traveler information media (*1*). These media can include Highway Advisory Radio (HAR), 511, websites, and commercial radio. Dudek (*4*) provides additional guidance on message length, the number of information units in a message, and message phrasing.

Credibility is an important factor in the use of CMSs. Many factors can cause reduced message credibility including inaccurate, outdated, irrelevant, obvious, repetitive, trivial, or poorly designed messages (*4*). The accuracy and relevance of information such as travel time are important, because they can be easily checked by drivers. If the information is proven incorrect, sign credibility will suffer. Reduced credibility can cause drivers to distrust the system and ignore the sign.

Design Issues

There are two schools of thought concerning what to display on a CMS when no unusual conditions exist or when there are no essential messages to present: (1) always display a message on the CMS regardless of whether there is an incident or unusual condition and (2) display messages only when an incident or other situation warrants a message and blank the CMS at all other times. The advantage of displaying a message on the CMS regardless of whether there is an incident is that drivers will know that the CMS is functioning. However, only 10% to 15% of English and French drivers assume the CMS is broken when it is not displaying a message (*5*). (This result could be caused by the policy in these drivers' jurisdictions of blanking the screen when there are no unusual conditions.) The disadvantage is that drivers may come to ignore the sign entirely if safety campaign or other non-traffic-related messages are displayed when no unusual conditions exist (*1*).

Thus, this guideline recommends displaying a message only when an incident warrants it and a blank CMS at other times. This policy is followed by 77% of transportation agencies surveyed in a 1997 national survey of 26 agencies (*1*). It also follows the human factors principles of CMS operation: don't tell drivers something they already know and use CMS only when a driver response is required (*4*).

Cross References

Determining Appropriate Message Length, 19-6
Composing a Message to Maximize Comprehension, 19-8

Key References

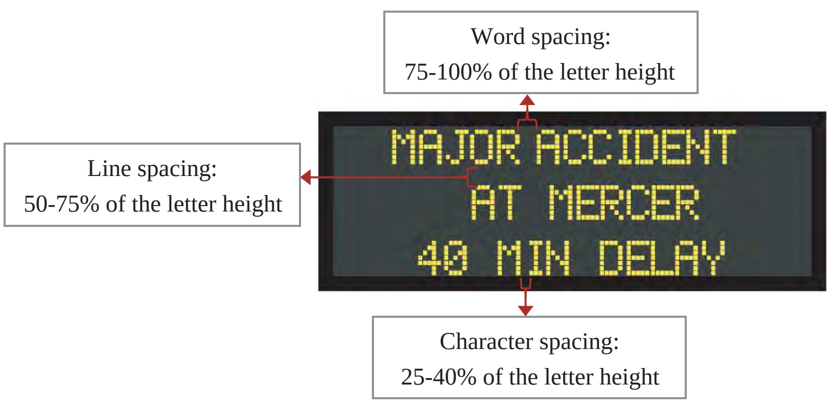
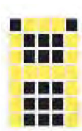
1. Johnson, C.M. (2001). *Use of Changeable Message Sign (CMS)*. FHWA Policy Memorandum response to James A. Cheatham. Retrieved June 19, 2008 from http://www.fhwa.dot.gov/legsregs/directives/policy/pame.htm.
2. Richards, S.H., and Dudek, C.L. (1986). Implementation of work zone speed control measures. *Transportation Research Record, 1086*, 36-42.
3. Halloin, D.M. (1996). Impediments to the effective use of portable variable message signs at freeway work zones. In C. Dudek (Ed.). *Compendium of Graduate Student Papers on Advanced Surface Transportation Systems* (pp. Ci-C34). College Station: Texas A&M University.
4. Dudek, C.L. (2004). *Changeable Message Sign Operation and Messaging Handbook*. (FHWA-OP-03-070). College Station: Texas Transportation Institute.
5. Montoro, L., Lucas, A., and Blanch, M.T. (2004). Specific design parameters: VMS Part I. In *The Human Factors of Transport Signs* (pp. 185-198). CRC Press.

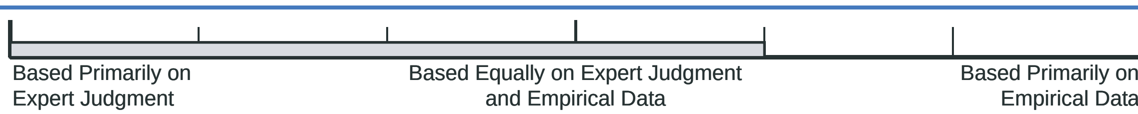
PRESENTATION TO MAXIMIZE VISIBILITY AND LEGIBILITY

Introduction

Presentation to maximize visibility and legibility refers to how the photometric and physical characteristics of a CMS can be employed to positively affect readability. Because CMS characters or symbols are typically constructed using a relatively coarse matrix of pixels, the requirements for their visibility and legibility are more demanding than for standard, fixed signs. Also, the fixed matrix introduces limitations to character size, height-to-width ratio, spacing, and other geometric characteristics available for presenting messages. The MUTCD provides specific guidance about letter height, minimum legibility distance, and other characteristics. Additional recommendations for designing messages within the limitations imposed by CMS technologies, including guidelines for contrast ratio, luminance, character spacing, and resolution are provided below.

Design Guidelines

<table>
<tr><th>CMS Characteristic</th><th colspan="4">Guideline Value</th></tr>
<tr><td rowspan="1">Contrast Ratio (light-emitting CMS)</td><td colspan="4">Optimal contrast ratio range = 8-12
where:
$$\textit{Contrast ratio} = \frac{\textit{Luminance}_{max}}{\textit{Luminance}_{min}}$$
Luminance_{max} = luminance emitted by the area or element of greatest intensity (text)
Luminance_{min} = luminance emitted by the area or element of least intensity (background)</td></tr>
<tr><td rowspan="3">Luminance (light-emitting CMS in cd/m²)</td><td></td><td>Sun Overhead</td><td>Overcast/Rain</td><td>Nighttime</td></tr>
<tr><td>Young (16-40)</td><td>850</td><td>350</td><td>30</td></tr>
<tr><td>Old (65+)</td><td>1000</td><td>600</td><td>30</td></tr>
<tr><td>Character Spacing (matrix CMS)</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Character Resolution</td><td colspan="4">Size should be consistent within a display</td></tr>
<tr><td colspan="2">
5 × 7 matrix: static or non-critical text</td><td colspan="2">
7 × 9 matrix: dynamic or critical text</td></tr>
</table>



Discussion

Contrast ratio: The photometric and physical properties of signs directly affect the legibility of the sign elements. For example, contrast ratios are affected by photometric properties such as luminance, but can be reduced by physical properties such as dirty or scratched protective plexiglass sheeting (*1*). The guidance on acceptable ranges depends on the conditions present in the ambient environment and whether the CMS is light reflecting or light emitting. Light-emitting CMSs have minimum contrast ratios on sunny days when the sun increases the background sign luminance, whereas light-reflecting CMSs have minimum contrast ratios when the light falling on the sign is at a minimum (*2*). Weather conditions such as rain and fog can affect contrast ratios for both types of signs by reducing the illumination coming from the sign or light reflected by the sign. The optimal contrast ratio range is between 8 and 12, although Dudek (*1*) presents other acceptable ranges based upon European research.

Luminance: Driver age and sun position affect the required CMS luminance significantly (*3*). Generally, greater luminances are required for older drivers than for younger drivers at a given distance. Garvey and Mace (*3*) found that during extreme backlit (sun behind the sign) and washout (sun directly on the sign) conditions, 1000 cd/m^2 is a minimum value. However, at 650 feet, some drivers cannot be accommodated under these visibility conditions, at any luminance level. If luminance values are too high at night, the characters may appear to *irradiate* or bleed onto the background and blur due to the extreme contrast (*4*).

Character spacing: Character spacing is limited by physical properties of the sign such as the matrix pattern of the LEDs. The spacing used should allow drivers to recognize (1) words as items rather than series of individual letters and (2) lines as separate entities. The included guidance is based upon the MUTCD, though Dudek (*4*) presents different values based upon the United Kingdom's draft CMS standards.

Character resolution: Character resolution can affect the readability of text. Campbell, Carney, and Kantowitz (*5*) reported that for characters smaller than approximately 22 arcminutes, a 7 × 9 matrix led to faster reading times and fewer reading errors than a 5 × 7 matrix. A 7 × 9 matrix should be used to display dynamic or critical text, while a 5 × 7 matrix can display static or non-critical text. There are obvious trade-offs between the resolution used and the amount of text that can be fit on the sign.

Design Issues

Appropriate resolution is also affected by the case of the characters presented. All uppercase letters are often displayed on CMSs and are more difficult for people to read than mixed or lowercase letters (*6*). People are more accustomed to reading mixed or lowercase letters and can identify word shapes using the ascenders and descenders. However, lowercase letters require a higher resolution matrix (5 × 9) to accommodate these descenders (*7*). The readability of lowercase letters also depends on the display of curved lines, which is a challenge on matrix displays. Thus, there are trade-offs between readability and practicality for displaying letters in mixed cases.

There are many types of CMSs available that utilize different technologies. Upchurch, Armstrong, Baaj, and Thomas (*8*) evaluated shuttered fiber-optic, LED, and flip disk signs to analyze the legibility distance of each. For backlit (sun directly behind sign) and nighttime conditions, LED and fiber-optic signs had better legibility distances than flip disk signs. For washout (direct sunlight on sign) and midday conditions, fiber-optic signs performed best for legibility distance. LED signs may interact negatively with sunglass filters. Sunglass lenses that have a notch filter, which attenuates light emissions in the same range that amber LEDs emit light (*9*), reduce the brightness of the LED, thereby decreasing the contrast and making CMS messages difficult to read.

Cross References

Key Components of Sight Distance, 5-2
Sign Design to Improve Legibility, 18-4
Composing a Message to Maximize Comprehension, 19-8

Key References

1. Dudek, C.L. (1997). *NCHRP Synthesis of Highway Practice 237: Changeable Message Signs*. Washington, DC: Transportation Research Board.
2. Dudek, C.L. (2004). *Changeable Message Sign Operation and Messaging Handbook.* (FHWA-OP-03-070). College Station: Texas Transportation Institute.
3. Garvey, P.M. and Mace, D.J. (1996). *Changeable Message Sign Visibility.* (FHWA-RD-94-077). Washington, DC: FHWA.
4. Dudek, C.L. (1992). *Guidelines on the Use and Operation of Changeable Message Signs*. (FHWA-TX-92-1232-9). College Station: Texas Transportation Institute.
5. Campbell, J.L., Carney, C., and Kantowitz, B.H. (1998). *Human Factors Design Guidelines for Advanced Traveler Information Systems (ATIS) And Commercial Vehicle Operations (CVO),* (FHWA-RD-98-057). Washington, DC: FHWA.
6. Proffitt, D.R., and Wade, M.M. (1998). *Creating Effective Variable Message Signs: Human Factors Issues.* (VTRC 98-CR31). Charlottesville: Virginia Transportation Research Council.
7. Hitchins, D. (2001). Lowercase font set development for variable message signs (VMS). *Proceedings of the 8th World Congress on Intelligent Transport Systems* [CD-ROM].
8. Upchurch, J., Armstrong, J.D., Baaj, M.H., and Thomas, G.B. (1992). Evaluation of variable message signs: target value, legibility, and viewing comfort. *Transportation Research Record, 1376*, 35-44.
9. Halloin, D.M. (1996). Impediments to the effective use of portable variable message signs at freeway work zones. In C. Dudek (Ed.). *Compendium of Graduate Student Papers on Advanced Surface Transportation Systems* (pp. Ci-C34). College Station: Texas A&M University.

DETERMINING APPROPRIATE MESSAGE LENGTH

Introduction

Determining the appropriate message length for a CMS refers to choosing a message length that drivers have the time to comprehend as they pass the sign. Controlling message length is extremely important because there is a limited amount of time to present information to drivers. Message length is described not only by the absolute length in the number of words, but also by the number of information units included in these words. Information units are a measure of the message load, or total amount of information in the message. If there are too many words or information units in a message, it may need to be split into two phases. Dudek (*1*) provides additional guidance for reducing message length and splitting long messages.

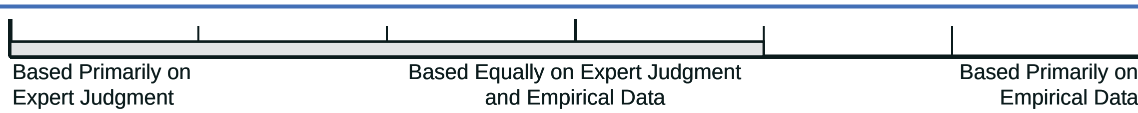
Design Guidelines

<table>
<tr><th>Message Property</th><th>Guidelines</th><th>Example (from Dudek (1))</th></tr>
<tr><td>Information Units:
A measure of the amount of information presented in terms of facts used to make a decision; a single information unit consists of 1 to 4 words</td><td>Use no more than:
• 2 information units per line
• 3 information units per phase (see below)
• 4 information units per message read at speeds of 35 mi/h or more
• 5 information units per message read at speeds less than 35 mi/h</td><td><table><tr><th>Question</th><th>Answer
(1 information unit)</th></tr><tr><td>What is the problem?</td><td>MAJOR ACCIDENT</td></tr><tr><td>Where is the problem?</td><td>AT US-23</td></tr><tr><td>Who is the message for?</td><td>NEW YORK</td></tr><tr><td>What should they do?</td><td>USE I-280 EAST</td></tr></table></td></tr>
<tr><td>Length:
Number of words or characters in a message, excluding prepositions</td><td>Use no more than:
• Eight words per message for drivers at high speeds (based on the required reading time of 1 s per four- to eight-character word, excluding prepositions, or 2 s per information unit, whichever is longest)</td><td>

Acceptable message length because the preposition “to” does not count.</td></tr>
<tr><td>Phases:
Similar to a page of a book, a phase is the text that is displayed at a single point in time</td><td>• Two phases maximum per message
• Each phase must be able to be understood alone
• One line should not contain parts of 2 information units but may contain 2 whole information units
• When dividing messages between two phases, compatible information units should be kept on the same phase</td><td>Poorly designed message:


Improved message:

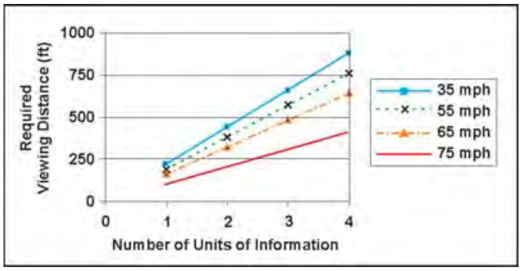
</td></tr>
</table>



Discussion

Information units: The recommendations for the number of information units that are appropriate for display are based on research and operational experience (*1*). Dudek (*2*) summarizes that 1 s is needed per four- to eight-character word excluding prepositions or 2 s per information unit, whichever is **longer**. Using this assumption, the required viewing distance for different numbers of information units, for drivers traveling at different speeds, are included below.

REQUIRED VIEWING DISTANCE PER NUMBER OF INFORMATION UNITS AT VARYING SPEEDS (ADAPTED FROM DUDEK (*1*))



However, the MUTCD (*3*) states that the minimum phase display time should be based upon 1 s per word or 2 s per information unit, whichever is **shorter**. This direct contradiction of Dudek (*2*) causes practical consequences for drivers. If the longer time is used (*2*) and the message includes many short words that do not all need to be remembered, the phase display time could be unnecessarily inflated. If the shorter time is used (*3*) and the message includes information units composed of multiple important words, drivers may not have time to read all of them. If longer messages need to be provided, they should be shown in conjunction with other information media (See *When to Use Changeable Message Signs*, 19-2).

Length: Dudek (*1*) states that the appropriate absolute message length is affected by (1) the amount of time that the driver is in the legibility zone of the CMS, considering travelling speed and environmental conditions; (2) the driver workload including all driver activities such as reading signs, lane positioning, etc.; and (3) message familiarity because drivers take more time to read unfamiliar content or unusual messages

The eight-word maximum for high speeds is based on the *legibility distance*, or the distance at which the words on the sign become legible, as well as the speed that the driver is travelling. This recommendation assumes drivers are traveling at 55 mi/h and the legibility distance of the sign is 650 ft (which is the approximate legibility distance for a lamp matrix sign with 18-in. character heights) (*2*). If the message is too long for drivers to read at normal speeds, it is likely that some drivers will slow down to be able to read the message, affecting the traffic flow (*1*). In general, the message length should be reduced as much as possible without losing the message intent (*1*). The message length can be reduced by the use of alternative phrases or appropriate abbreviations and the removal of redundant and unimportant information.

Phases: Dudek (*1*) reports that research has shown drivers have difficulty reading messages that are on more than two phases. Because either the first phase or the second phase may be read first by a passing driver, each phase should make sense by itself. This is accomplished by keeping compatible information units in the same phase. In addition, portions of two different information units should not be displayed on a single line because it is confusing to drivers and increases reading time (*1*).

Design Issues

The legibility distance for a CMS is affected by a number of factors. If the sign is placed off to the side of the roadway rather than directly over the travel lanes, additional sight distance is required (*1*) because a driver's field of view is assumed to be between 10° right and left of head-on. Proffitt and Wade (*4*) support rotating the CMS 5° to 10° toward the roadway to increase the amount of time that roadside signs are at an optimal reading angle. However, conflicting ideas exist regarding the assumed angular range of the legibility distance. This distance is also affected by lighting conditions, sun position, vertical curvature, horizontal curvature, spot obstructions, rain, fog, and trucks in the traffic stream (*1*). If the legibility distance of the sign is reduced, then the time that the driver has to read the sign is reduced, necessitating a reduction in the number of information units contained on the sign.

Cross References

Key Components of Sight Distance, 5-2
Changeable Message Signs, 13-6
When to Use Changeable Message Signs, 19-2
Presentation to Maximize Visibility and Legibility, 19-4
Composing a Message to Maximize Comprehension, 19-8
Displaying Messages with Dynamic Characteristics, 19-10

Key References

1. Dudek, C.L. (2004). *Changeable Message Sign Operation and Messaging Handbook.* (FHWA-OP-03-070). College Station: Texas Transportation Institute.
2. Dudek, C.L. (1992). *Guidelines on the Use and Operation of Changeable Message Signs*. (FHWA-TX-92-1232-9). College Station: Texas Transportation Institute.
3. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
4. Proffitt, D.R., and Wade, M.M. (1998). *Creating Effective Variable Message Signs: Human Factors Issues.* (VTRC 98-CR31). Charlottesville: Virginia Transportation Research Council.

COMPOSING A MESSAGE TO MAXIMIZE COMPREHENSION

Introduction

Composing a CMS message to maximize comprehension refers to message formatting issues that affect driver understanding or reading times. Driver comprehension is important because the message may provide a legitimate safety warning that requires the driver to take an action. Drivers have a limited amount of time to comprehend the information and make a decision. Messages that are easy to comprehend reduce the amount of time required to read and grasp the meaning of the message, facilitate decision making, and promote faster responses. The following guidelines can be used to increase driver comprehension of signs.

Design Guidelines

<table>
<tr><th>Message Property</th><th>Guidelines</th></tr>
<tr><td>Abbreviations</td><td>

Avoid using abbreviations whenever possible.
If abbreviations are necessary, use approved abbreviations from Section 1A.14 of the MUTCD.
If the MUTCD does not include the desired abbreviation, create an abbreviation by removing letters from the end of a word until it is the desired length.
</td></tr>
<tr><td>Date/Day Format</td><td>

If the dates are in the next week:

– Use days of the week rather than calendar dates (e.g., “Tue – Thur”)

– Do not use “For 1 Week” because the start and end dates are ambiguous

– “Nite” may be used in place of “Night”

– A hyphen with a space on either side may be used in place of “Thru”

– “Weekend” may be used if the event begins on Saturday morning and ends on Sunday evening
If the dates are not in the next week:

– Use a three-letter month abbreviation rather than a numerical month representation (i.e., “Apr 21” rather than “4/21”)

– Only state the month once if both dates in a range are in the same month (i.e., “Apr 21 – 23” rather than “Apr 21 – Apr 23”)

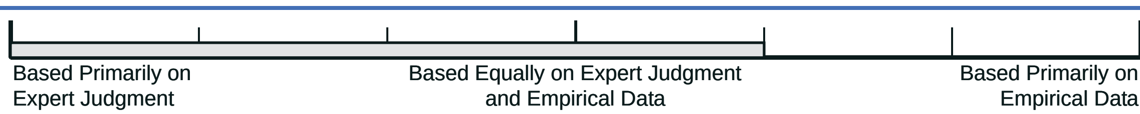
– Don’t include day, date, and time information
</td></tr>
<tr><td>Element Order</td><td>Recommended precedence order for message elements is shown below. Note that only a limited number of elements should be included in a single message (adapted from Dudek (1)).
<table>
<tr><th>Message Element</th><th>Element Description</th></tr>
<tr><td>1. Incident/Roadwork/ Closure Descriptor</td><td>Description of the unusual situation (use closure descriptor when all lanes on the roadway or ramp are closed)</td></tr>
<tr><td>2. Incident/Roadwork/ Closure Location</td><td>Location of the unusual situation</td></tr>
<tr><td>3. Lanes Closed/Blocked</td><td>Description of the exit ramps or lanes that are closed or blocked; can be used instead of Element 1</td></tr>
<tr><td>4. Effect on Travel</td><td>Description of the severity of the situation to help the driver decide whether or not to divert (e.g., delay or travel time)</td></tr>
<tr><td>5. Audience for Action</td><td>Used when the action applies to a subset rather than all drivers</td></tr>
<tr><td>6. Action</td><td>Tells drivers what to do</td></tr>
<tr><td>7. Good Reason for Following the Action</td><td>Gives drivers confidence that following the action will improve safety or save time</td></tr>
</table></td></tr>
<tr><td>Justification</td><td>Use staircase indentation for rows:

1) Justify top row at left

2) Center middle row

3) Justify bottom row at right</td></tr>
<tr><td>Message Specificity</td><td>

Provide specific diversion or incident location information when available.
Use the phrase “This Exit” instead of the phrase “Next Exit” to refer to the upcoming exit.
</td></tr>
</table>



Discussion

Abbreviations: Abbreviations provide the benefit of reduced message length; however, their use is discouraged because they have been found to decrease message comprehension (*2*) and increase reading times (*3*). However, due to fixed sign size and message length recommendations, abbreviations can be necessary to convey the information to the level of specificity desired. Proffitt and Wade (*3*) report that in a study of sonar operators, viewers preferred truncated abbreviations over conventional (created by experts) or contraction (vowel removed) abbreviations. Truncated abbreviations proved to have faster response times and improved decoding times with subsequent trials.

Date format: Research has shown that drivers have difficulty converting calendar dates to appropriate days of the week (*1*). However, it is often desirable to present closure or other information more than 1 week in advance, necessitating the inclusion of numeric date information in the message. In a laptop study examining date formats, Ullman, Ullman, and Dudek (*9*) found that regardless of the format that was used to present the day and date information, only approximately 75% of drivers could tell if the event would impact their current or future travel.

Element order: The order of elements in a message varies widely depending on what information is known and appropriate to describe the incident. The MUTCD (*4*) suggests that on portable message signs, the message be as brief as possible and contain three elements: the problem, the location or distance to the problem, and the recommended driver action. This recommendation loosely maps to the recommended order of message elements by Dudek, included on the previous page (*1*).

Justification: Greenhouse (*2*) found that staircase-justified messages increase reader comprehension, perhaps because this style better matches drivers' eye movements as they read the message. This recommendation contradicts the MUTCD standard that all text should be center justified (*4*).

Message specificity: Message specificity is a message property that is affected by many different message aspects including space available on the sign, the information available to the Traffic Management Center, information unit limits, and message length limits. Wang, Collyer, and Yang (*8*) found through participant questionnaires that more specific messages (i.e., "Accident at Exit 12/Major Delays to Boston/Use Route I-295") are preferred to less specific messages (i.e., "Accident at Exit 12/Major Delays/Use Other Routes"). Pedic and Ezrakhovich (*5*) also report that drivers are more likely to correctly interpret a message when it includes a specific diversion task instead of a generic task. Drivers are also more willing to divert if given the incident location, expected delay, and best detour strategy rather than just a subset of that information (*6*). Survey data show that precise location information was preferred so drivers could make informed decisions about exiting/re-entering the roadway (*7*). When expressing exit information, "This Exit" instead of "Next Exit" was preferred to refer to the upcoming exit (*7*).

Design Issues

When used in messages, signal words (e.g., "Danger," "Warning," "Caution") may not be interpreted as intended and do not affect driver performance (*3*). Avoiding the use of such words can reduce reading time, conserve sign space, and prevent driver confusion.

Sign comprehension also depends on driver literacy. Weak readers depend more on the message context for comprehension, are more affected by text degradation (similar to bulb burn-out on CMS), and hold more parts of a message in memory at a single time due in part to slower reading (*3*). Thus, Proffitt and Wade (3) recommend the use of context about the message subject, standardized message formats to enhance familiarity, and distinct directional statements. Because there is no literacy test required for driver licensing, message composition should accommodate varying reading competencies.

Another aspect that affects comprehension is the use of symbols. Symbols can convey information without requiring driver literacy. In general, symbolic signs are recognized better, faster, and from further away than the corresponding text signs (*3*). However, care should be taken in their use because the meaning of symbolic signs is not always as well understood. Using a CMS to display television pictures of conditions or maps was not positively received by a majority of survey respondents (*7*).

Cross References

Driver Comprehension of Signs, 18-8
Presentation to Maximize Visibility and Legibility, 19-4
Presentation of Bilingual Information, 19-14

Key References

1. Dudek, C.L. (2004). *Changeable Message Sign Operation and Messaging Handbook.* (FHWA-OP-03-070). College Station: Texas Transportation Institute.
2. Greenhouse, D. (2007). *Optimizing Comprehension of Changeable Message Signs (CMS).* (UCB-ITS-PRR-2007-24). Berkeley: University of California Partners for Advanced Transit and Highways (PATH).
3. Proffitt, D.R., and Wade, M.M. (1998). *Creating Effective Variable Message Signs: Human Factors Issues.* (VTRC 98-CR31). Charlottesville: Virginia Transportation Research Council.
4. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
5. Pedic, F., and Ezrakhovich, A. (1999). A literature review: The content characteristics of effective VMS. *Road & Transport Research, 8*(2), 3-11.
6. Peeta, S., Ramos, J.L., and Pasupathy, R. (2000). Content of variable message signs and on-line driver behavior. *Transportation Research Record, 1725*, 102-108.
7. Benson, B.G. (1996). Motorist attitudes about content of variable-message signs. *Transportation Research Record, 1550*, 48-57.
8. Wang, J.-H., Collyer, C.E., and Yang, C.-M. (2005). *Enhancing Motorist Understanding of Variable Message Signs.* (FHWA-RIDOT-RTD-06-1). Providence: Rhode Island Department of Transportation.
9. Ullman, G.L., Ullman, B.R., and Dudek, C.L. (2007). Evaluation of alternative dates for advance notification on portable changeable message signs in work zones. *Transportation Research Record, 2015*, 36-40.

DISPLAYING MESSAGES WITH DYNAMIC CHARACTERISTICS

Introduction

Dynamic characteristics refer to message properties that specify character movement. These characteristics include the time to display each message phase, blanking between phases of a multi-phase message, flashing one or more lines of a message, alternating lines in multi-phase messages, and *looming* (making text or symbols increase in size over time). Improper use of dynamic message characteristics can lead to increased reading times and reduced message comprehension.

Design Guidelines

Topic	Definition	Guideline	Rationale/Source
Phase Display Time	The amount of time to display each phase of a two-phase message	Use whichever is longest: • 2 s per information unit *or* • 1 s per four- to eight-character word (excluding prepositions)	Research and field experience (*1*)
Blank Time between Phases	The amount of time that a CMS is left completely blank between message phases	Insert a 300 ms blank screen between message phases 1 and 2.	Increased word and number comprehension (*3*)
Flashing Messages	One-phase messages that flash the entire message	Do not use.	Disagreement in research results (*4*, *5*)
	One-phase messages that contain one flashing or blinking line	Do not use.	Increased reading time and reduced comprehension (*4*, *5*)
Alternating-Line Messages	Multiple-phase messages in which only a subset of the lines change between phases	Do not use.	Increased reading time (*4*, *5*)
Looming	Increasing text or symbol size over time	Do not use.	No positive effect (*3*)

BLANK TIME BETWEEN CYCLES (FROM DUDEK (*1*))

TYPE OF CMS	EXAMPLE	BLANK TIME BETWEEN CYCLES
One-word or one-line sign with three or more phases		0.25 s blank screen + 0.50 s screen with 3 asterisks + 0.25 s blank screen OR 0.25 s or less between phases + 1.00 s between cycles

EQUATION: HOW MUCH TIME SHOULD BE USED TO DISPLAY EACH PHASE?

1. Find the time that is available for the entire message T = total time available to read the message	$T(s) = \dfrac{\textit{Legibility Distance (ft)}}{\textit{Traveling Speed}\ (^{ft}/_{s})}$
2. Find the time that is needed for each phase x = number of information units in phase 1 y = number of information units in phase 2	*Time for phase* 1 $(t_1) = 2x$ *Time for phase* 2 $(t_2) = 2y$
3. Make sure that the time required is less than or equal to the time available B = blanking time between phases	$T \geq B + t_1 + t_2$

Discussion

Only a limited amount of research has been conducted on the dynamic properties of message signs (*2*). In addition, most of the studies have been conducted in laboratory or simulator settings rather than on the road.

Phase display time: The amount of time that a single phase should be displayed is determined by the amount of content in that phase. Dudek (*1*) summarizes that either 1 s is needed per four- to eight-character word excluding prepositions or 2 s is needed per information unit, whichever is longest. The total time available to divide between the phases is reduced by the blank time between the phases, discussed below.

Blank time between phases: Greenhouse (*3*) found that inserting a 300 ms blank screen between phase 1 and phase 2 of a portable message sign improves comprehensibility. This improvement is possibly because a refractory period helps information processing between screens. Although this conclusion applies directly to portable message signs, it may be true for permanent message signs as well. Note that the blank screen was only tested between phase 1 and phase 2, not between phase 2 and phase 1 when the message cycled. It is unknown if providing a blanking time between phase 2 and phase 1 would provide a further benefit. It is reasonably conceivable that drivers who see a blank between phases 1 and 2, but not between phases 2 and 1, would reverse the order of the phases and possibly have trouble understanding the message. Dudek (*1*) recommends that blank time and/or asterisks be displayed between cycles of a message that contains three or more phases (on one-word or one-line signs). Because these signs are more limited in the amount of information that they can display at one time, the phases may not make sense independently and drivers who read later phases before phase 1 may not understand the message. Thus, giving an indication of where the message is in the cycle gives drivers an idea of their location in the cycle.

Flashing phase: There are many ways in which all or portions of messages can be flashed in an attempt to draw driver attention. One method is to flash the entire display for a one-phase message. Research (*4*, *5*) in laboratory and simulator settings disagreed with regard to the effects on comprehension and reading time. In the laboratory, comprehension was not affected, but reading times were significantly longer when the message was flashing. In the simulator, comprehension was negatively affected for unfamiliar drivers, but reading times were not affected. Full-phase flashing messages are not recommended because of this disagreement in research results.

Flashing line: Another flashing method is to flash one line of a message. Research in laboratory and simulator settings (*4*, *5*) showed that comprehension levels and reading times were both negatively affected by this method. Thus, flashing one line is not recommended.

Alternating line: In alternating-line messages, a portion of the message is held constant between the two phases (usually the first two lines) while the other portion is alternated between two pieces of information (usually the third line). Research (*4*, *5*) on this method showed that although comprehension was not affected, reading times greatly increased.

Looming: In a study by Greenhouse (*3*), looming was shown to negatively affect some driver demographics more than others. However, it did not help any group of drivers comprehend messages. It also seemed to function as an additional driver distraction and a negative effect on intelligibility.

Design Issues

None.

Cross References

Composing a Message to Maximize Comprehension, 19-8

Key References

1. Dudek, C.L. (1992). *Guidelines on the Use and Operation of Changeable Message Signs*. (FHWA-TX-92-1232-9). College Station: Texas Transportation Institute.
2. Dudek, C.L. (2004). *Changeable Message Sign Operation and Messaging Handbook.* (FHWA-OP-03-070). College Station: Texas Transportation Institute.
3. Greenhouse, D. (2007). *Optimizing Comprehension of Changeable Message Signs (CMS).* (UCB-ITS-PRR-2007-24). Berkeley: University of California Partners for Advanced Transit and Highways (PATH).
4. Dudek, C.L., and Ullman, G.L. (2002). Flashing messages, flashing lines, and alternating one line on changeable message signs. *Transportation Research Record, 1803*, 94-101
5. Dudek, C.L., Schrock, S.D., and Ullman, G.L. (2005). *Impacts of Using Dynamic Features to Display Messages on Changeable Message Signs*. (FHWA-HOP-05-069). Washington, DC: FHWA.

CHANGEABLE MESSAGE SIGNS FOR SPEED REDUCTION

Introduction

CMSs for speed reduction refers to situations in which a reduction in the speed of the traffic flow is desirable due to potential hazards, work zones, adverse weather conditions, incident control, or heavy congestion. Applications that are temporary or variable in nature are the primary candidates for using a speed-reduction CMS. Areas that experience recurring heavy peak traffic also can benefit from the proper application of a speed-controlling CMS.

Design Guidelines

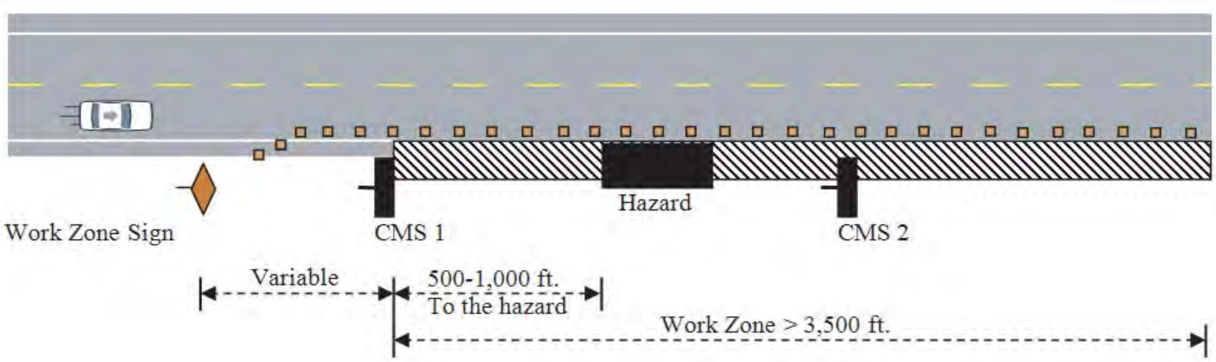
General CMS Applications for Speed Reduction:

- Provide a reason for the reduced speed.
- Limit the use of safety campaign messages.
- Use CMS with radar for speed reduction:
  - "You Are Speeding/Slow Down" is an effective message for speeders (*5*).
  - "Your Speed/XX mph" is the MUTCD-approved text for displaying approach speeds.

Work Zone CMS Applications for Speed Reduction:

- In work zones over 3500 ft, use a second CMS partway through.
- For extended work (i.e., 1 year), use CMS for the project opening days and after major condition changes. Use passive controls at other times.
- Place the first CMS 500-1000 ft upstream from the hazardous location within the work zone after the first advance sign.
- Place signs away from other work zone signs, ramps, intersections, or lane-closure tapers.

SIGN PLACEMENT IN A WORK ZONE



Source: adapted from the MUTCD (6)

MAXIMUM SPEED REDUCTIONS IN WORK ZONES

Roadway Type	Speed Reduction (mi/h)
Rural two-lane, two-way highway	10-15
Rural freeway	5-15
Urban freeway	5-10
Urban arterial	10-15

Source: Richards and Dudek (*4*)

Discussion

General applications: Speed-reduction CMSs are used to reduce speeds during a wide range of events such as potential hazards, adverse weather conditions, traffic incidents, and heavy congestion. When CMSs are provided to reduce driver speeds, compliance is increased when a reason for the reduced speed is displayed (*1*). These signs are still effective after 7 weeks of exposure, continuing to cause significant speed reductions (*2*). In a simulator study by Jamson and Merat (*3*), little change in driver behavior was observed when the safety campaign message "Watch Your Speed" was displayed (maximum 0.5 mi/h speed reduction). However, it was found using eye-tracking data that drivers continued to look at CMSs along the route even though the message was repeated. Drivers who witnessed 33% of the CMSs on the route displaying safety campaign messages changed lanes significantly faster in response to an incident message than those who saw either all blank CMSs or 100% of the CMSs showing safety messages. These drivers also spent significantly more time looking at the incident message than any other group. An FHWA Policy Memorandum states that driver safety campaign messages should be limited to a few weeks so that drivers do not begin to ignore them (see "When to Use Changeable Message Signs" on page 19-2).

CMSs can also use radar to reduce speeds. Garber and Srinivasan (*2*) refer to a number of studies that show CMS with radar to be effective in reducing passing vehicle speeds. The message "You Are Speeding/Slow Down" proved to be the most effective message for reducing speeds (*5*). This message reduced average speeds, 85th percentile speeds, and traffic speed variance by statistically significant amounts. The MUTCD states that for these signs, the legend "Your Speed/XX mph" or something similar should be shown (*6*).

Work zone applications: CMSs have a limited range of effectiveness. The first CMS should be positioned 500 to 1000 ft upstream from the hazard in a work zone to give drivers time to react before reaching that hazard. However, this distance cannot be too long because drivers need to remember the message and maintain the reduced speed when they reach the hazard. In longer work zones, drivers tend to increase their speeds when they near the end of the zone, far away from the first CMS (*2*). Thus, if hazards continue to exist throughout a long zone, a second CMS may be needed.

The visibility and prominence of CMSs are important. Ideally, drivers will not be overloaded with information and will have sufficient available attention to focus on the CMS (*4*). Thus, the guidance is to place the CMS away from work zone signs, and out of high driver workload areas such as ramps, intersections, or lane-closure tapers.

Credibility is a general issue with CMSs that also applies to the application of CMSs in work zones. The selection of an unreasonably low speed causes drivers to lose respect for the signs, which leads to a loss of credibility (*4*). This loss of credibility can lead to reduced effectiveness of signs at other sites as well.

Richards and Dudek (*4*) report that drivers will only slow down a limited amount regardless of the posted limit. The reductions in average work zone speeds were found to be 5-20 mi/h, depending on the site. Thus, Richards and Dudek suggest maximum speed reductions in work zones as shown in the table on page 19-12.

Design Issues

Speed reductions as supported by CMSs can cause reductions in roadway capacity and congestion (*4*).

Cross References

Changeable Message Signs, 13-6
When to Use Changeable Message Signs, 19-2
Displaying Messages with Dynamic Characteristics, 19-10

Key References

1. Pedic, F., and Ezrakhovich, A. (1999). A literature review: The content characteristics of effective VMS. *Road & Transport Research, 8*(2), 3-11.
2. Garber, N.J., and Srinivasan, S. (1998). *Effectiveness of Changeable Message Signs in Controlling Vehicle Speeds in Work Zones—Phase II*. (FHWA/VTRC 98-R10). Charlottesville: Virginia Transportation Research Council.
3. Jamson, A.H., and Merat, N. (2007). The effectiveness of safety campaign VMS messages—A driving simulator investigation. *Driving Assessment 2007: 4th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 459-465.
4. Richards, S.H., and Dudek, C.L. (1986). Implementation of work-zone speed control measures. *Transportation Research Record, 1086*, 36-42.
5. Garber, N.J., and Fontaine, M.D. (1996). *Controlling Vehicle Speeds in Work Zones: Effectiveness of Changeable Message Signs with Radar*. (UVA/529242/CE96/102). Charlottesville: University of Virginia.
6. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.

PRESENTATION OF BILINGUAL INFORMATION

Introduction

Bilingual information refers to information that is presented in more than one language on CMSs. Drivers spend 10% to 15% more time reading bilingual than monolingual signs if they have more than 1 line in each language (*1*). However, in areas with large culturally diverse populations or areas with heavy international tourism, signs that present messages in more than one language may be required. Presenting bilingual information on a sign can increase reading times for monolingual and bilingual drivers. It is important to minimize this increase in reading times to reduce driver distraction.

Design Guidelines

Guideline	Example (adapted from Jamson (*1*))
• Group lines by language rather than content – Display the most widely spoken language first	
• Distinguish between languages on signs with two or more lines of text per language by using: – Case: display one language in all uppercase and the other in initial case (first letters of words capitalized)	
– Color: display one language in one color and the other in a different color	
– Spacing: leave a row blank between message lines in different languages	

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

Discussion

Reading response time for one line of relevant text on a two-line bilingual sign is not significantly different than reading response time for a one-line monolingual sign (*1*). Also, none of the demarcation techniques for the different languages made an impact on reading times for two-line bilingual signs. However, reading response times for two lines of relevant text on a four-line bilingual sign are significantly longer than reading response times for a two-line monolingual sign. The time required to read two lines of relevant text on a four-line bilingual sign is comparable to the time required to read four lines on a monolingual sign. Thus, introducing two lines of a second language strongly impacts reading performance. This impact can be mitigated through any of the demarcation techniques of color, case, or spacing.

Learning and expectancy effects were tested for case, color, and language order (*1*). Case showed neither effect, suggesting that drivers did not notice that it was being used to distinguish between languages. Color showed only expectancy, meaning that reading times did not decrease as more signs were viewed with the same color pattern, but times significantly increased when that pattern reversed. Language order showed both effects, showing that drivers learned the pattern and then were confused when it changed. These results speak to the effectiveness of different demarcation methods as well as the importance of consistency across bilingual message signs in an area.

Reading time is minimized when the dominant language of the driver is positioned first on the sign, for signs containing either one or two lines of relevant text per language (*1*). This finding has also been verified for static signs in both English/Welsh and English/French. The effect is greater for monolingual readers, based on bilingual readers in the English/French study seeming to respond to whichever language was first on the sign.

The studies that are cited on bilingual messages were performed using English and Welsh, which have identical character sets. Identical character sets lead drivers and study participants to attempt to read both sets of messages before finding one illegible (*2*). Results may not hold for bilingual signs displaying languages that use more distinctive character sets. Additionally, most of the guidance provided above is based upon a single, computer-based study.

Design Issues

Multiple methods were suggested by Jamson (*1*) for distinguishing between messages in different languages. Although the methods were proven to provide benefits for drivers, care should be used when applying some of these techniques. When the languages are distinguished by color, the colors selected should have neutral or equal meaning to drivers (*1*). For example, red can imply urgency, causing drivers to perceive the message in one language as more urgent. The colors should also have equal luminance in changing light and weather conditions. Language differentiation by case has disadvantages as well. Some studies indicate that mixed font is easier to read, while words written in all capital letters could be seen as higher priority. Also, displaying lowercase letters requires more space on the CMS to accommodate the descenders. Providing a blank row between languages has been shown to improve glance legibility (*1*). The greatest benefit was provided to monolingual drivers, especially when their language was not dominant. Multiple methods can be used concurrently to distinguish between languages; however, these effects were not studied.

An additional issue is the splitting of bilingual messages into multiple phases. The phase guidelines from Determining Appropriate Message Length (page 19-6) should be taken into consideration. Jamson (*1*) found that if a four-line bilingual message is split into two phases in such a way that each phase contains one line in each language that does not make sense alone, reading times for both phases increase significantly. The concern with presenting the entire message in one language and then another language (each phase is monolingual) is that drivers may encounter the sign when it is not displaying a language that they understand while other drivers, who could comprehend the message, may already be reacting in ways that are unexpected (*1*).

Cross References

Determining Appropriate Message Length, 19-6

Key References

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CHAPTER 20

Markings

VISIBILITY OF LANE MARKINGS

Introduction

Visibility of lane markings refers to the ease with which drivers can see and follow longitudinal lane markings. Lane markings are designed for a certain *preview time*, the amount of time that drivers look ahead on the roadway. This preview time is affected by the distance at which drivers can see markings, which is a function of retroreflectivity and marking width. Different lane marking patterns and colors can have different meanings and regulate different driver actions, such as exiting, lane changing, passing, and maintaining roadway position. For this and other safety reasons, it is important that drivers are able to see and understand lane markings from an appropriate distance.

Design Guidelines

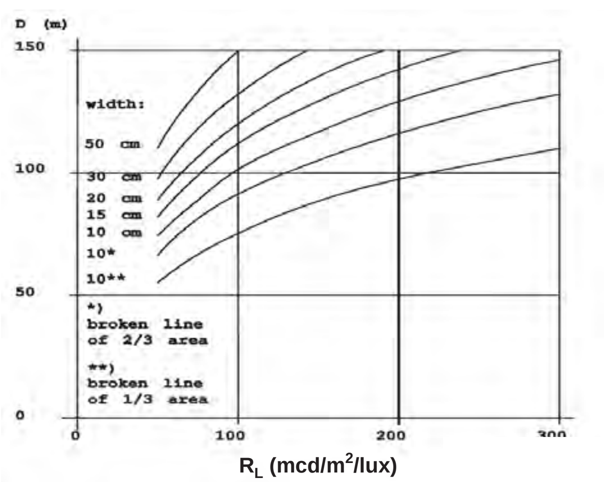
Factor	Guideline
Preview Time	• Absolute minimum preview time = 3 s • Recommended preview time = 5 s
Marking-Specific Luminance	• Minimum Dark Luminance = 100 mcd/m^2/lux • Minimum (adjusted for dirt) Dark Luminance = 121 mcd/m^2/lux
Marking Width	• If there is concern about the visibility of the markings, use a 6 or 8 in. marking width instead of the standard 4 in.

mcd = millicandela

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

MATHEMATICAL ESTIMATION OF VISIBILITY DISTANCE BASED UPON MARKING RETROREFLECTIVITY AND WIDTH (1) (MODELS ARE FOR YOUNG DRIVERS AND DO NOT CONSIDER GLARE)

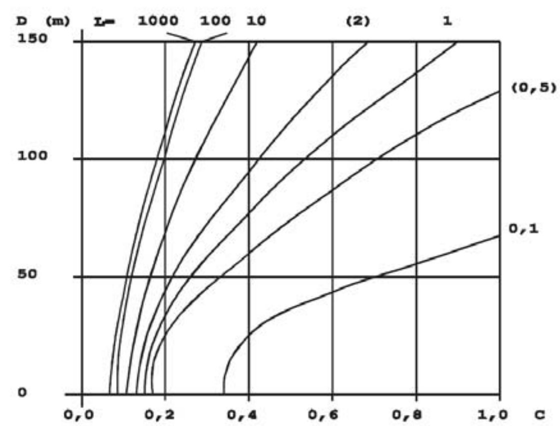
Visibility distance (D) for longitudinal road markings in high-beam illumination



Where:

- R_L is the coefficient of retroreflected luminance (and R_L (road) = 15 mcd/m^2/lux)
- Luminous intensity is constant towards the road markings (10,000 cd)

Visibility distance (D) for a continuous road marking of 10 cm width in uniform illumination (simulated daylight)



Where:

- C is the contrast ratio between the pavement marking and the roadway
- L is the luminance in cd/m^2

(Note: Road surface luminance levels in Europe typically range from 0.5 to 2 cd/m^2.)

Discussion

Preview time: There is some disagreement regarding the minimum amount of preview time that should be provided for drivers. Rumar and Marsh (*2*) determined through a literature review that a 5-s preview time accommodates proper anticipatory steering behavior, safe steering on roads that are not straight, and the minimum long-range preview time. However, the same review revealed that the Commission Internationale de l'Eclairage (CIE) recommended a lower bound of 3 s for preview time. Schnell and Zwahlen (*3*) suggest adding an 85th percentile eye-fixation duration of 0.65 s to the 3-s minimum chosen by the CIE to account for the time required for the driver to see and process the marking information. This value is also supported by the COST study, which found that drivers initially had a 2.18-s average preview time, but when the visibility of road markings in the on-road study was increased, the preview times increased to 3.15 s on average (*1*). Additionally, drivers increased their speed very little to compensate for the increased marking visibility (equivalent to approximately 0.1 s of the time increase) and thus preserved the remainder of the preview time. Therefore, this recommendation is to provide a 5-s preview time when possible, but a 3-s preview time as an absolute minimum.

Retroreflectivity: Pavement line retroreflectivity affects the distance from which drivers can view a pavement marking. In a study using subjective observer ratings, Graham, Harrold, and King (*4*) found that 85% of participants 60 years of age and older rated markings with retroreflectance values of 100 mcd/m^2/lux or greater as being adequate or more than adequate when viewed under nighttime conditions. They also calculated a 21% increase in this value (to 121 mcd/m^2/lux) to account for occluded light due to dirty windshields and headlights for vehicles that are reasonably maintained. Additionally, more than 90% of the young subjects rated a marking retroreflectance of 93 mcd/m^2/lux as adequate or more than adequate for night conditions. In another study utilizing subjective ratings, Ethen and Woltman (*5*) also found 100 mcd/m^2/lux to be the minimum for dark conditions. Note that the luminances that were rated as acceptable were much higher (300 to 400 mcd/m^2/lux) in comparison to the minimum values (*5*).

Marking width: The standard width for most longitudinal pavement markings is 4 in. In a survey of state highway agencies, 58% have used markings that are wider than the standard 4-in. marking for centerline, edge line, or lane line applications (*6*). The data are limited regarding the effectiveness of these markings. However, when surveyed, drivers placed high priority on the quality of pavement markings (*6*). A variety of studies have shown that when wider than standard pavement markings were used, mean lateral placement was more centered, fewer lane departures on curves were observed, and lanekeeping in low-contrast situations improved (*6*). Gates and Hawkins (*6*) concluded that these wider markings show benefits for locations where a higher degree of lane or roadway definition is needed, such as in horizontal curves, roadways with narrow or no shoulders, and construction work zones. Although many of these findings result from a test of one width (either 6 or 8 in.), Gibbons, McElheny, and Edwards (*7*) found that visibility distance increased for a 6-in. width, but not correspondingly for the 8-in. width. This finding suggests that there may be a threshold where performance does not significantly increase with an increase in line width.

Design Issues

Problems with glare are more pronounced with the elderly, because optical deficiencies of the eye increase with age. In addition to the temporal visual impairments, glare can cause discomfort and fatigue. In a simulator study with a 4-in. edge line and opposing headlamp glare conditions, subjects aged 65 to 80 required an increase in contrast of 20% to 30% over a younger sample to correctly discern downstream curve direction. To accommodate less capable drivers, the study suggests an increase in stripe brightness of 300% (*8*).

Gates, Chrysler, and Hawkins (*9*) found that short-range driving performance, including activities such as lane positioning, is more reliant on driver peripheral vision than foveal vision. Wider markings are believed to provide a stronger signal to the driver's peripheral vision over standard width markings, thereby improving driver comfort and short-range performance. Most studies about marking width involve long-range driving tasks such as end detection, which are performed by foveal vision.

Cross References

None.

Key References

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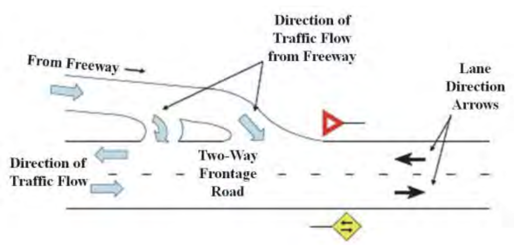
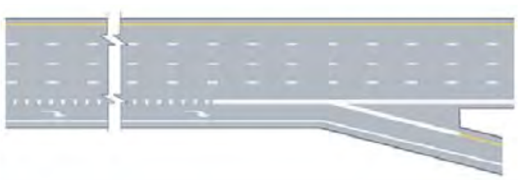
EFFECTIVENESS OF SYMBOLIC MARKINGS

Introduction

Effectiveness of symbolic markings refers to the degree to which drivers follow and understand text or symbols on the roadway. A major component of pavement markings is *horizontal signing*, which is composed of sign text that is painted on the roadway. Horizontal signing is effective because drivers spend most of their time scanning the roadway in front of their vehicle near the horizon (*1*). Because drivers are already looking at the pavement, they are likely to see information there more quickly, preventing the need for an eye movement away from the road. Additionally, the pavement can be a good location to provide lane-specific information.

Design Guidelines

Marking Goal	Do this:		Do *not* do this:	
Reduce speeds in horizontal curves	 Curve arrow and "50 mph" text	 "Curve 55 mph" text	 Transverse lines	 "Curve Ahead" text
Reduce wrong-way movements on two-way frontage roads	 Lane direction arrows on a two-way frontage road by an off-ramp		N/A	
Provide route guidance information for lane drops	 Route shield in the exiting lane		 Route name text in the exiting lane	
	 Pavement marking arrows (in addition to traditional lane drop markings)		N/A	

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

Discussion

Speed reduction in horizontal curves: In an on-road study of horizontal signing to reduce speeds before horizontal curves, Chrysler and Schrock (*1*) found that the text "Curve 55 mph" reduced speeds on a rural road by approximately 4 mi/h more than the control treatment. Although this finding was not statistically significant, the benefit from this marking was greater than for the "Curve Ahead" text (which did not cause a significant reduction). When the curve arrow and "50 mph" text were tested on an urban roadway, vehicles significantly reduced their speeds by 10% at the entrance to the curve. There was also an 11% to 20% reduction in vehicles exceeding the speed limit. Note that the curve arrow and "50 mph" text were tested in a section of the road following a vertical crest, so the arrow provided additional information about the direction of the curve after drivers came over the crest. Another option if advisory speeds cannot be displayed is the text "SLOW" with a curve arrow. Retting and Farmer (*2*) tested this marking on a suburban road and found that it significantly reduced the percentage of drivers exceeding the speed limit by more than 5 mi/h during the daytime and late night time frames, but not during the evening. Overall, the markings that provided advisory speeds or an action performed most effectively.

The results of transverse line treatments have been mixed. Chrysler and Schrock (*1*) found that a series of three pairs of transverse lines near the middle of the lane did not cause a significant speed reduction. However, Katz (*3*) found that transverse lines at the lane edges resulted in speed reductions, which were significant on interstate and arterial roadways, but not rural roadways. Note that the treatments differed in multiple ways. Chrysler and Schrock (*1*) attempted to create a "visual rumble strip," which would appear in the driver's foveal vision, on a rural road. Katz (*3*) used markings at the lane edges, which would appear in the driver's peripheral field of view and create the illusion of higher than actual speed.

Wrong-way movements on two-way frontage roads: Chrysler and Schrock (*1*) tested the implementation of lane direction arrows on a frontage road in Texas. The use of one-way and two-way frontage roads is widespread in Texas, potentially increasing the probability of wrong-way movements. Lane direction arrows were placed on the frontage road, 120 ft from the gore area of the exit onto the road. With the arrows installed, the rates of wrong-way driving maneuvers and conflicts were significantly reduced by 90% and almost 100% respectively. This overwhelming reduction in wrong-way driving indicates that the treatment can have a beneficial safety influence on traffic at locations where drivers may be confused about appropriate lane selection.

Lane drops: In a study of route guidance information regarding lane drops, Chrysler and Schrock (*1*) surveyed drivers about route markers. The majority (94%) of respondents preferred the route shield over the route name text. However, 29% to 48% of drivers thought that the marking indicated the route they were currently on rather than the upcoming exit. Therefore, route shields may be effective when used with other lane drop signs/markings. Fitzpatrick, Lance, and Lienau (*4*) tested another lane drop indicator: pavement marking arrows. With the addition of pavement marking arrows, erratic maneuvers such as lane changes through the gore and attempted lane changes decreased. Drivers continuing on the main route moved out of the exit lane earlier. Although these results were only significant for two out of the three sites tested, the other site had a lane drop only 1.6 km (1 mi) long, and vehicles may have shifted through the exit lane upstream of the study segment.

Design Issues

Horizontal signing has two issues that can be broadly applied: visibility of the markings and durability of the materials on the travel lane. Horizontal markings viewed during daytime must contrast with the road surface. White markings may not provide an adequate contrast for symbol recognition or word legibility when viewed against a concrete or worn asphalt surface. Conversely, nighttime visibility is affected by the durability of the optical elements presented in the marking material, typically glass beads. Other visibility limitations can be found in shortened headways due to traffic congestion that may not be large enough for full horizontal sign viewing. Horizontal signs should have large simple components and should be visually unique to the highest possible degree. Proper application using text or symbols should minimize the use of abbreviations, keeping the symbols simple and legible. By limiting the application to critical locations, drivers will be able to recognize these signs as an added warning or caution (*5*).

Chrysler and Schrock (*1*) determined that when drivers are undergoing stressful driving conditions or situations where too much information is presented at one time, they will practice "load shedding" by ignoring the least important information and focusing on the more important tasks. Drivers will tend to look at the road more and at side or overhead-mounted signing less when "load shedding" takes place. This behavior increases the importance of horizontal signing in the area where drivers look most.

Cross References

None.

Key References

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MARKINGS FOR PEDESTRIAN AND BICYCLIST SAFETY

Introduction

Markings for pedestrian and bicyclist safety refers to pavement marking techniques to encourage safe practices for road sharing by vehicles, pedestrians, and bicycles. Pedestrian markings include crosswalks, which are defined as marked or unmarked extensions of sidewalks or shoulders across intersections (*1*). Crosswalks may also be located midblock, but only if marked. Bicycles and vehicles may utilize shared lanes on either rural or non-rural roadways. The purpose of markings in shared lanes is to notify users that the lane is shared and clearly define the positioning of the traffic flows.

Design Guidelines

RECOMMENDATIONS FOR INSTALLING MARKED CROSSWALKS AND OTHER PEDESTRIAN IMPROVEMENTS AT UNCONTROLLED LOCATIONS

Roadway Type (Number of travel lanes and median type)	Vehicle ADT ≤ 9,000			Vehicle ADT > 9,000 to 12,000			Vehicle ADT > 12,000 to 15,000			Vehicle ADT > 15,000		
	≤ 30 mi/h	35 mi/h	40 mi/h	≤ 30 mi/h	35 mi/h	40 mi/h	≤ 30 mi/h	35 mi/h	40 mi/h	≤ 30 mi/h	35 mi/h	40 mi/h
2 lanes	C	C	P	C	C	P	C	C	N	C	P	N
3 lanes	C	C	P	C	P	P	P	P	N	P	N	N
Multilane (≥ 4 lanes) with raised median	C	C	P	C	P	N	P	P	N	N	N	N
Multilane (≥ 4 lanes) without raised median	C	P	N	P	P	N	N	N	N	N	N	N

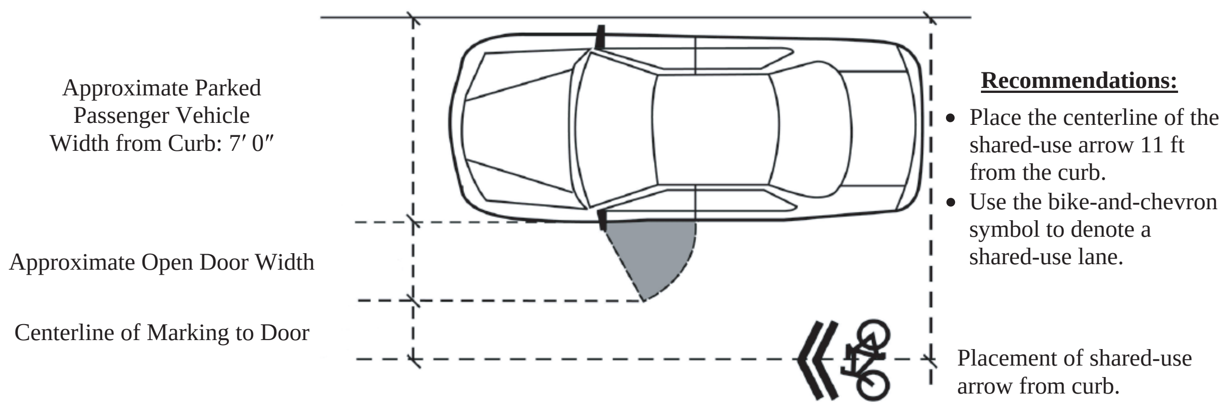
C: Candidate site for marked crosswalk. Marked crosswalk can be considered after an engineering study and confirmation of 20 pedestrian (or 15 elderly/child) crossings per peak hour.

P: Possible increase in pedestrian crash risk may occur if crosswalks are added without other crossing improvements; locations should be monitored and enhanced with other improvements if necessary before adding a crosswalk.

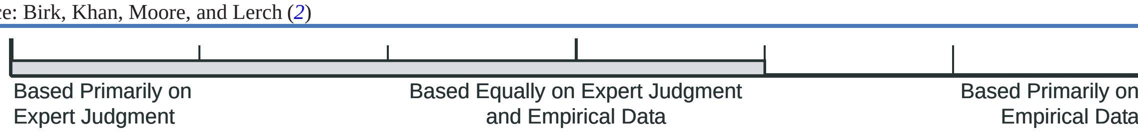
N: Marked crosswalks should not be added alone because pedestrian crash risk may increase; treatments such as traffic calming measures, traffic signals with pedestrian signals, or other crossing safety improvements should be considered.

Source: adapted from Zeeger et al. (*1*)

PLACEMENT OF RECOMMENDED SHARED-USE LANE SYMBOL FOR BICYCLISTS AND VEHICLES



Source: Birk, Khan, Moore, and Lerch (*2*)



Discussion

Crosswalks: Zeeger et al. (*1*) provide guidelines for the locations where marked crosswalks should be installed based upon a study of pedestrian crashes at marked and unmarked crosswalks. The guidelines apply to uncontrolled locations excluding school crossings. Crosswalks should not be installed in locations where additional pedestrian safety risks exist (e.g., poor sight distance, confusing designs) without other design features or traffic control devices (*1*). Crosswalks alone do not make crossings safer or guarantee that more vehicles will stop for pedestrians.

Nowakowski (*3*) found that there are three critical locations where potential vehicular-pedestrian conflict could occur: the mid-block crossing and the left and right turning lanes at an intersection. The difficulty for the driver is detecting pedestrians because visual scanning and attention are limited. It is recommended that parking be eliminated on the approach to uncontrolled crosswalks to improve vision between pedestrians and drivers. The Uniform Vehicle Code (*4*) specifies that parking should be prohibited within 20 ft of a crosswalk at an intersection (which could be increased to 30 to 50 ft in advance of a crosswalk on a high-speed road).

Design of the shared-use arrow: Shared-use arrows (also referred to as "sharrows") on roadways attempt to reduce safety problems such as "dooring," where bicyclists ride into parked vehicle doors when ajar; wrong-side riding; sidewalk riding; motorists squeezing out bicyclists; and other aggressive behaviors (*2*). Shared pavement markings can increase the percentage of bicyclists riding in the street, which can help reduce crashes with turning vehicles.

Two bicyclist surveys and an on-road study regarding a number of shared-lane markings were conducted in San Francisco (*2*, *5*). The lane markings tested were bike-and-chevron (shown on the previous page), bike-in-arrow (bicyclist inside of an arrow outline), and a separated bike-and-arrow. During the on-road study, the bike-and-chevron marking significantly reduced sidewalk riding (by 35%) and wrong-way riding (by 80%). It also increased all distances between moving cars, cyclists, and parked cars. Overall, 60% of cyclists thought that the markings positively affected their sense of safety and preferred the bike-and-chevron marking by a 2:1 ratio. However, 30% of cyclists indicated that the markings tested meant that bikes have priority, rather than that the lane is shared.

The distance of the shared-use arrow from the curb is based upon parked vehicle width. Birk et al. (*2*) observed that the 85th percentile of car doors open 9 ft 6 in. from the curb, the average bicycle width is 2 ft, and 6 in. of "shy distance" is added between the open door and bicycle handlebars. In total, these distances indicate that the centerline of the pavement marking should be 11 ft from the curb.

Design Issues

Crosswalk lighting: In-roadway crosswalk warning lights can provide pedestrian safety benefits. With in-roadway warning lights: passing vehicle speeds decreased from 7% to 44% (*6*, *7*), the percentage of drivers yielding to pedestrians increased during day and night by 26% to 162% (*8*, *9*), and the percentage of drivers who saw the crosswalk, saw a pedestrian, and accurately stated the presence of the pedestrian increased by 13%, 25%, and 38%, respectively (*8*).

Shared lanes: Shared-use lanes often exist where there is too little space available to create a dedicated bicycle lane. When space is available, a bicycle lane or wide curb lane may be created; however, there is disagreement as to which is better. See Hunter, Stewart, Stutts, Huany, and Pein (*10*) for a discussion of each lane type.

Cross References
None.

Key References

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POST-MOUNTED DELINEATORS

Introduction

Post-mounted delineators (PMDs) are a type of retroreflective marking device mounted above the roadway surface and along the side of the roadway in a series to indicate the alignment of the roadway. Delineators are particularly useful at locations where the alignment might be confusing or unexpected, such as at lane reduction transitions and/or curves (*1*). They are also useful at night and during adverse weather. Delineators may be used on long sections of highways or on short sections where there are changes in horizontal alignment. An important advantage of delineators is that they remain visible when the roadway is wet or snow covered.

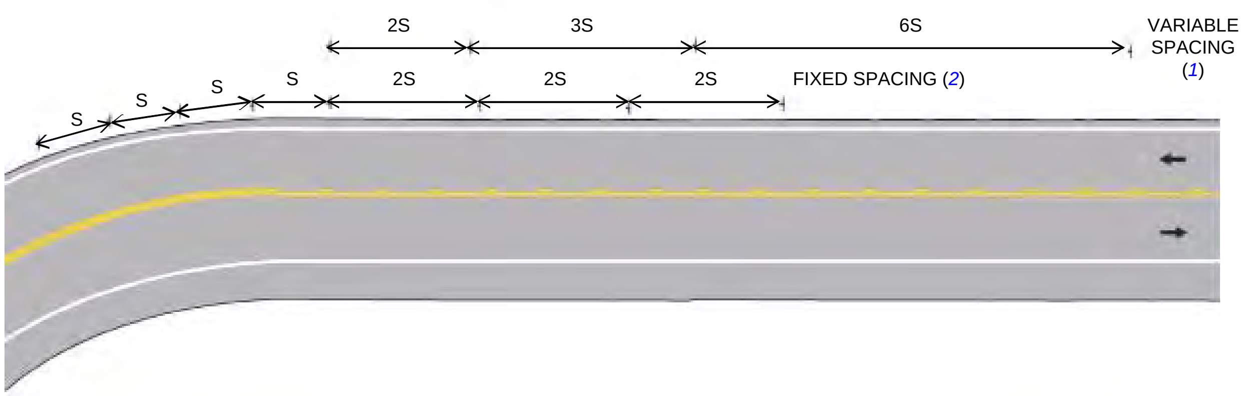
Design Guidelines

Spacing: Drivers respond similarly to fixed and variable spacing of delineators when perceiving curvature. Thus, either spacing method can be used for outlining the curve approach and departure segments.

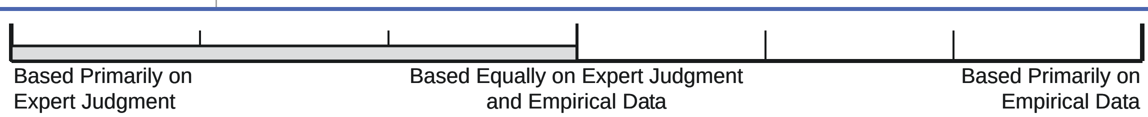
MUTCD (*1*) RECOMMENDATIONS FOR DELINEATOR SPACING ON CURVES

Radius of Curve (ft)	50	115	180	250	300	400	500	600	700	800	900	1000
Approximate Spacing (S) on Curve (ft)	20	25	35	40	50	55	65	70	75	80	85	90

VARIABLE AND FIXED SPACING FOR CURVE APPROACHES AND DEPARTURES



Preview Times	Post-mounted delineators should be visible with a preview time of at least 5 s.
Number of Reflectors	There is no difference in curve perception between single and double delineators; thus, either is acceptable for curve delineation.
Color	Drivers are not aware of the varying meanings of differently colored delineators. If differently colored delineators are used, drivers should receive education as to their specific meanings.



Discussion

Spacing: Charlton (*3*) found that drivers' perceptions of speed and curvature appear to work at both a conscious (explicit) and unconscious (implicit) level. For this reason, curve warnings and delineation treatments that highlight the sharpness of the curve ahead or increase a drivers' momentary sense of their apparent speed appear to offer promise in allowing drivers to enter curves at a lower speed. Delineation treatments may also assist drivers with selecting and maintaining appropriate lane position while travelling throughout the curve.

Chrysler, Carlson, and Williams (*2*) found that drivers cannot distinguish between fixed and variable delineator spacing on the approaches to horizontal curves. The two types of spacing led to functionally equivalent curve perceptions. Thus, Chrysler et al. (*2*) recommend that the approach and departure delineator spacings be fixed at two times the appropriate curve spacing found in the MUTCD. This recommendation can save installation time without sacrificing safety. More specific information on spacing on horizontal curves can be found in the MUTCD.

Preview time: Rumar and Marsh (*4*) explained two complementary road guidance functions: short-range and long-range guidance. Long-range guidance (over 5 s of preview time) allows the driver to consciously predict the path of the roadway far in advance, drive smoothly, and avoid time-pressure situations. Rumar and Marsh (*4*) found that preview times provided by lane markings alone are well under a safety criterion of 5 s and thus concluded that current lane markings are not optimal for safe night driving. Good & Baxter (*5*) found the addition of PMDs tends to have a positive effect for long-range guidance, but have no effect on short-range guidance. To be usable for long-range guidance, PMDs should be visible at a preview time of at least 5 s (about 440 ft at 60 mi/h (140 m at 100 km/h)) under low-beam illumination.

Number of reflectors: Chrysler et al. (*2*) found that the perception of curvature is not affected by the number of reflectors on the delineator. However, the combination of one reflector and variable spacing leading up to the curve caused the perception of less curvature. Overall, Chrysler et al. (*2*) recommend that the MUTCD eliminate the distinction between the two types of delineators and define a standard delineator. Larger delineators could still be used for emphasis where necessary.

Color: Chrysler et al. (*2*) found that drivers do not understand the difference in placement for yellow and white delineators. Although response accuracy was poor for curve delineator color, when given a forced-choice question regarding crossover delineation, most drivers could recognize the correct color. This finding led to the recommendation of putting more emphasis on delineator color in driver education courses rather than altering the MUTCD.

Design Issues

Another use of delineators is to define the roadway leading up to a railroad grade crossing. At rural crossings without active warning devices, the lighting may be poor and drivers may be more reliant on auditory train signals to know if a train is approaching. However, these auditory signals may not be completely effective for drivers who are hearing impaired. Staplin, Lococo, Byington, and Harkey (*6*) found that approximately 30% to 35% of people aged 65 to 75 have a hearing loss, increasing to 40% for persons over the age of 75. The use of post-mounted delineators would help highlight to hearing-impaired drivers that railroad crossing is imminent.

Cross References

None.

Key References

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MARKINGS FOR ROUNDABOUTS

Introduction

Markings for roundabouts refers to pavement markings on the entrances to and exits from roundabout intersections. Roundabout intersections are defined by the MUTCD (*1*) as "circular intersections with yield control at entry, which permits a vehicle on the circulatory roadway to proceed, and with deflection of the approaching vehicle counter-clockwise around a central island." Roundabout markings need to display clear information to incoming drivers to ensure the safe circulation of vehicles. Conflict points occur where one vehicle path crosses, merges, or diverges with or queues behind the path of another vehicle, pedestrian, or bicycle. Within roundabouts, fewer conflict points occur as compared to conventional intersections; hazardous conflicts such as right-angle and left-turn head-on crashes are eliminated. Single-lane approach roundabouts provide greater safety benefits than multilane approaches because there are fewer potential conflicts between road users, and pedestrian crossings are shorter. Robinson et al. (*2*) note that lower vehicle speeds entering and in the roundabout provide drivers more time to deal with potential conflicts.

Design Guidelines

Luminance contrast between the curb markings and the pavement should be:

- 2.0 or higher for roundabouts with overhead lighting
- 3.0 or higher for roundabouts without overhead lighting

Luminance contrast is calculated by:

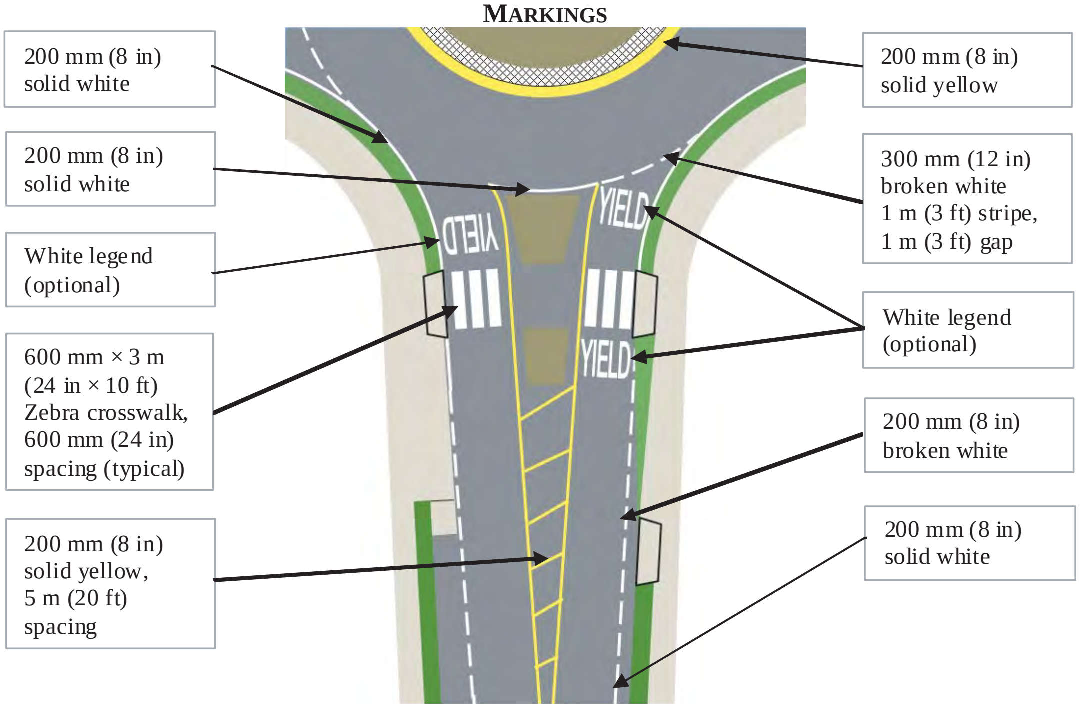
$$\text{Luminance contrast} = \frac{L_{stripe} - L_{pavement}}{L_{pavement}}$$

Where:

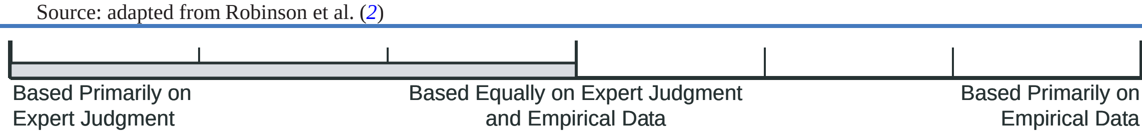
L_{stripe} = the luminance of the pavement marking

$L_{pavement}$ = the luminance of the pavement

RECOMMENDED ROUNDABOUT PAVEMENT MARKINGS



Source: adapted from Robinson et al. (*2*)



Discussion

Luminance contrast: Staplin, Lococo, Byington, and Harkey (*3*) recommended that retroreflective markings should be applied to the sides and tops of the curbs on the splitter islands and the central island. The recommended curb contrast levels refer to the contrast between these markings and the pavement. For roundabouts with overhead lighting, a contrast of 2.0 or higher was recommended. For roundabouts without overhead lighting, a contrast of 3.0 or higher was recommended. Staplin et al. (*3*) state that the luminance measurements should be taken at night, using low-beam headlamp illumination from a passenger vehicle, at a 5-s preview distance upstream of the intersection.

Recommended roundabout pavement markings: The pavement markings in the figure shown on the previous page are from *Roundabouts: An Informational Guide* (*2*) and differ slightly from those included in the MUTCD (*1*). Several markings are usually placed within roundabouts to help regulate the flow and speeds of oncoming vehicles. Such markings include broken white lines, solid white lines, solid yellow lines, crosswalk markings, and roadway marking text "Yield". Roundabout lane markings follow the logic that yellow lines denote opposing traffic and white lines denote traffic moving in the same direction. A solid white line marks the right edge of the road. Additionally, normal or fish-hook lane-use arrow pavement markings may be used on roundabout approaches as defined by the MUTCD (*1*).

A fundamental difference between roundabouts and traditional intersections is the continuous flow of traffic at roundabouts vs. the alternating of opposing traffic flows at traditional intersections (*2*). This difference creates different visual demands at roundabouts, where the driver is not given the right-of-way by traffic signals. Also, pedestrians are not given signaled time to cross roundabouts. The placement of crosswalks at roundabouts is further back in order to move pedestrians out of the continuous traffic flow. This placement also reduces the visual demands for drivers who otherwise would be required to look for approaching vehicles from the left and pedestrians from the right as they entered the roundabout. With the crosswalk further from the circular area, pedestrians cross in the drivers' forward field of vision (*2*).

Crosswalks: It is important that the crosswalks preceding the roundabout have a high degree of visibility because they are set back from the yield line. Zebra crossings are recommended because they are highly visible, distinguish the intersection from signalized intersections, and are less likely to be confused with the yield line than transverse crosswalks (*2*).

Bicycle lanes: The MUTCD (*1*) states that bicycle lane markings shall not be included within the circulatory roadway of a roundabout. The figure on the previous page shows how Robinson et al. (*2*) suggest that bicycle lanes should be included on an approach to a roundabout. This design provides a curb ramp where the bicycle lane ends to allow bicyclists to transition as a pedestrian to the sidewalk. Robinson et al. (*2*) state that, at roundabouts, bicyclists can circulate with other vehicles, travel as a pedestrian on the sidewalk, or use a separate shared-use facility for pedestrians and bicyclists where provided.

Design Issues

Stopping sight distance: Stopping sight distance should be provided at every point within a roundabout and on each entrance and exit (*2*). On the approach to the roundabout, vehicles need to have a stopping sight distance to the crosswalk and the yield line. When circulating, vehicles need to be able to see that same distance around the circle. When exiting the roundabout, vehicles need a stopping sight distance to the crosswalk. The intersection sight distance is the distance that a driver without the right-of-way needs in order to see and react to conflicting vehicles before entering the roundabout (*2*). Because of the geometry of the roundabout, the intersection sight distance implies drivers must look over/through part of the central island. This requirement poses restrictions on the height and placement of objects and landscaping in that island; appropriate sight distance requires a clear central island. However, Robinson et al. (*2*) recommends that only the minimum intersection sight distance should be provided because excessive sight distance can lead to higher vehicle speeds, reducing safety for all users.

Cross References

None.

Key References

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CHAPTER 21

Lighting

COUNTERMEASURES FOR MITIGATING HEADLAMP GLARE

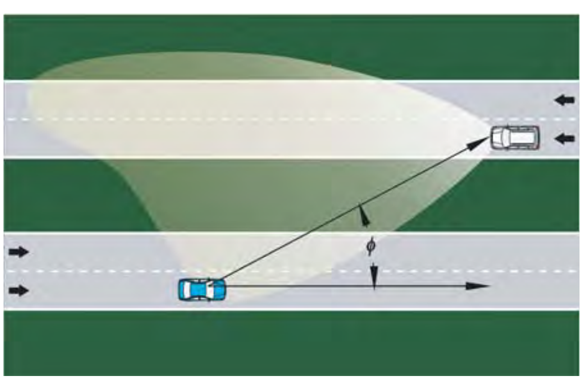
Introduction

Countermeasures for mitigating headlamp glare refers to road design elements that are effective for reducing the discomforting and disabling effects on visibility of exposure to glare from oncoming headlamps. The combination of high-intensity headlamps and high mounting heights in the vehicle fleet can result in greater exposure to glare for motorists. Several treatments are available for designing roadways that can reduce drivers' exposure to glare.

Design Guidelines

The following table presents advantages and disadvantages of various treatments for mitigating glare.

Treatment	Advantages	Disadvantages
Wide medians	• Greater glare angle reduces the glare effect • Increased object contrast due to reduced background luminance	• Increased cost of construction, extra right-of-way purchase, median landscaping, and maintenance • Increased time to cross an intersection may lead to less efficient traffic signal operation
Independent alignments	• Can completely eliminate view of oncoming vehicle and associated glare • Less earthwork required on slopes and other topographies, allowing flexibility in design • More environmentally friendly	• Longer construction time compared to narrow median designs • Larger right-of-way requirement
Glare screens	• Effectively reduces glare • Installation can be limited to specific problem areas • Simple to install and maintain • Reasonable cost	• Requires some type of barrier on which to install the screen • Effective only when the vehicles are on the same level plane • Do not work well with significant vertical curves
Fixed roadway lighting	• Improved visibility of objects and pedestrians • Increased adaptation level reduces glare effect	• High cost (installation, operation, and maintenance) • Potential for crashes with lighting pole (mitigated with break-away mountings & greater setback)



The Commission Internationale de l'Eclairage (CIE) veiling luminance model below shows that veiling luminance increases as glare angle θ decreases. Wide medians reduce veiling luminance by increasing θ (1).

$$\frac{L_{veil}}{I_{glare}} = \frac{10}{\theta^3} + \left[\frac{5}{\theta^2}\right] \cdot \left[1 + \left(\frac{A}{62.5}\right)^4\right]$$

Where:

I_{glare} = luminous intensity of glare source
θ = glare angle
A = driver age

Discussion

Glare occurs when the intensity of a light source within the visual field is substantially greater than the visual adaptation level, causing physical discomfort or pain (discomfort glare) and/or reduced visibility (disability glare). A portion of the light entering the eye is scattered in the transparent media of the eye (i.e., cornea, lens, and vitreous fluids) and by the tissues in the ocular fundus (*2, 3*). Some light also diffuses through the sclera and iris tissues. The scattered light superimposes a uniform veiling luminance onto the retinal image, reducing its overall contrast. If the contrast of an object falls below the contrast threshold under these conditions, it will be rendered invisible. Furthermore, transient adaptation caused by rapid changes in luminances within the visual field can cause further temporary reductions in contrast sensitivity and form perception (*4*). The amount of veiling luminance produced by headlamp glare is influenced primarily by headlamp characteristics—such as mounting height, beam pattern, and misaim—and by the angle at which the glaring luminance enters the eye.

Design Issues

Several mathematical models have been developed that estimate the amount of veiling luminance developed by a glare source (e.g., *1*, *5*, *6*). These models show that veiling luminance is inversely proportional to the angle at which the glaring luminance enters the eye relative to the forward gaze. Consequently, the glaring effects of exposure to light from oncoming headlamps can be significantly reduced by increasing the lateral separation of the opposing vehicles via wide median widths and independent alignments (*7*). Increasing the lateral distance between vehicles results in larger glare angles and therefore smaller veiling luminances. Independent alignments can separate vehicles both horizontally and vertically, and in some cases can eliminate exposure to oncoming glare altogether.

Other mitigations include the installation of glare screens (*8*) and fixed roadway lighting (*7*). Glare screens are devices used primarily in roadway medians to shield drivers' eyes from exposure to glare from the headlights of oncoming vehicles. Typical glare screens consist of solid partitions (with or without intermittent openings), expanded metal mesh, knit polyester fabric, or vertical paddles oriented at an angle that blocks oncoming glare but allows lateral visibility. The cutoff angle for these types of glare screens is typically 20 degrees plus the degree of roadway curvature. Although no specific warrants have been established for installation of glare screens, many factors should be considered when determining whether to install these screens. These factors include nighttime crash rates (e.g., day-night ratio, average age of drivers in nighttime crashes, distribution of crash type, etc.), high traffic volume, public comments, high measured veiling luminance, road geometry, etc. Care must be given when designing and implementing glare screens in order to avoid limiting the sight distance in horizontal curves.

Fixed roadway lighting can reduce the effects of glare by: (1) increasing the visibility of objects and pedestrians and (2) increasing the overall adaptation level.

Cross References

Characteristics of Effective Lighting at Intersections, 21-12
Nighttime Driving, 21-4

Key References

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2. Adrian, W., & Bhanji, A. (1991). Fundamentals of disability glare: A formula to describe straylight in the eye as a function of glare angle and age. *Proceedings of the First International Symposium on Glare*, 185-193. New York: Lighting Research Institute.
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NIGHTTIME DRIVING

Introduction

Nighttime driving refers to particular challenges to motorists' visibility while driving in darkness on rural roads. The farthest distance at which drivers can see roadway features, objects in the roadway, or pedestrians ahead is limited by the headlamp intensity, ambient lighting, and presence or absence of oncoming headlamp glare. Often in rural driving, the ambient illumination is of such low intensity that it has little effect on visibility. Illumination of problem areas along with appropriate signing can play a significant role in improving safety when driving at night.

Design Guidelines

The following treatments have been shown to reduce nighttime crashes and to promote speed reduction and stop compliance at rural intersections (*1*,*2*,*3*,*4*). It should be noted that the *Manual on Uniform Traffic Control Devices* (MUTCD) and state and local policies should always be consulted before treatments are selected.

Treatment Type	Suggested Conditions for Use	Benefits
Safety lighting	• Light conditions are dark • High pedestrian traffic • High average daily (or nightly) travel • Areas with high crash history or high potential for crashes	• Improved pedestrian and vehicle detection and recognition • Earlier reduced speed at intersections • Most effective for crash reduction
Advance warning signs	• Intersection approach • Sharp curve approach	• Potential for earlier reduced speed
Advance warning signs with post-mounted beacon	• Intersection approach • Sharp curve approach • Areas with crash history or potential for crashes	• Beacon captures attention, implies urgency, and improves sign conspicuity • Potential for earlier reduced speed
Stop sign with post-mounted beacon	• Intersection approach • Intersections that do not warrant continuous lighting • Areas with crash history or potential for crashes	• Beacon captures attention and improves sign conspicuity • Potential for earlier reduced speed
Reflective strips on Stop sign	• Unlighted or dark intersections • Minor leg of "T" intersection	• Improved conspicuity of the sign by increasing visible surface area
Raised pavement markers	• Light conditions are dark (with or without lighting) • Curves and tangents (see Chapter 6)	• Improved visibility of lane when road surface condition is wet
Intersection flashing beacons	• Intersections where continuous lighting is not cost effective • Pedestrian traffic • Areas with crash history or potential for crashes	• Beacon captures attention and provides alert for upcoming intersection • Potential for earlier reduced speed

Discussion

Visibility during nighttime driving in rural environments can be challenging for drivers. Often there is little or no ambient lighting to enhance the illumination of the roadway or objects thereon. Visibility distance is limited to a threshold imposed by the luminous intensity of the headlamps, beyond which roadway features and objects or persons in the roadway are not visible due to insufficient contrast. Depending on headlamp characteristics and object reflectivity, visibility is generally limited to between 150 and 250 ft under clear, dry conditions (*5*, *6*). However, the time required to react and stop under the best of conditions (i.e., short braking reaction time and hard deceleration) when driving at 55 mi/h can be 280 ft or more (*7*). Compounding this problem is the potential for increased stopping distance due to longer perception-reaction time caused by fatigue from prolonged rural driving.

Drivers often underappreciate the visual challenges associated with driving in darkness for several reasons. First, drivers believe they can safely drive at unsafe higher speeds because (a) there is sufficient light from the headlamps to support lane keeping, and (b) it is relatively easy to see road signs, edge lines, delineators, and other vehicles on the road (*6*). Also, the central vision required for hazard detection and recognition is severely degraded at distances beyond the visibility threshold of the headlamps (*6*). Drivers may not understand the illumination pattern of their own headlamps (i.e., that the illumination provided by the headlamp is heterogeneous) and may therefore misjudge the visibility distance within various regions of headlamp illumination (*8*). Speed limits that are uniform between day and night lead drivers to assume that driving at the speed limit is safe even though it may not be possible to stop within the visibility distance of the headlamp (*9*). Finally, drivers seldom use their high-beam headlamps, even in situations where there are no oncoming vehicles or vehicles in the lane ahead (*10*). Because of these factors, drivers often are likely to be unprepared for a dangerous encounter while driving in darkness.

Design Issues

Fixed roadway illumination can improve visibility, reduce speed, and improve safety in rural areas that are identified as potentially hazardous or that have significant crash histories (e.g., *3*, *4*). Although lighting is the most effective mitigation for improving visibility, alternative treatments, such as signing, reflectors, and beacons, can enhance safety by reflecting more existing light to drivers or alerting drivers in advance of upcoming features.

The warrant criteria for installing continuous lighting is usually based on an analysis of cost-effectiveness, considering installation, operation, and maintenance costs in addition to the cost associated with crashes (*2*, *3*). The warrant criteria vary widely between states and research sources and include factors such as average daily travel, crash frequency, and night-to-day crash ratio.

It may be appropriate to use a sign telling drivers to turn on their headlights when in the tunnel.

Cross References

Countermeasures to Improve Pavement Delineation, 6-10
Sign Design to Improve Legibility, 18-4

Key References

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DAYTIME LIGHTING REQUIREMENTS FOR TUNNEL ENTRANCE LIGHTING

Introduction

This guideline provides recommendations for minimum lighting requirements at the entrances of tunnels under daylight conditions. Visibility of low-visual-contrast objects can be challenging for drivers due to glare, large differences in illumination, and visual adaptation issues associated with the tunnel entrance. The guideline information below provides initial illumination recommendations that can be used during the initial tunnel design stage to promote better visibility when entering tunnels.

Design Guidelines

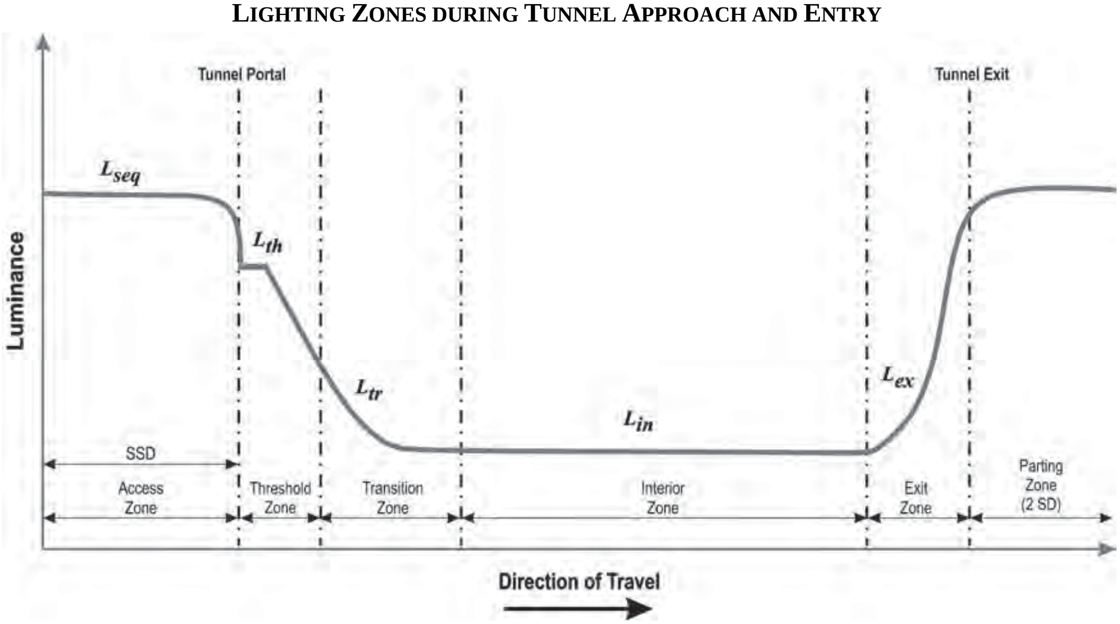
The table below provides general recommendations for initial luminance design. More precise calculations are recommended once the tunnel design is well defined (from IESNA (*1*)).

RECOMMENDED DAYTIME MAINTAINED AVERAGE PAVEMENT LUMINANCE LEVELS IN THE THRESHOLD ZONE OF VEHICULAR TUNNELS (L_{TH})

Approach Characteristics	Traffic Speed		Driver Direction		
	km/h	mi/h	North	East-West	South
			cd/m^2		
Open Road	100	60	250	310	370
	80	50	220	260	320
	60	40	180	220	270
Urban Tunnel	100	60	320	280	310
	80	50	280	240	270
	60	40	230	200	220
Mountain Tunnel	100	60	230	200	200
	80	50	200	170	170
	60	40	170	140	140

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

LIGHTING ZONES DURING TUNNEL APPROACH AND ENTRY



Source: adapted from CIE (*2*).

Discussion

Lighting of tunnel entrances requires special consideration because of how drivers' visual systems respond to the unique lighting conditions that occur at these entrances. In particular, there are driver performance issues related to illumination levels in tunnel entrances. The first issue is that glare from the bright visual zones surrounding the tunnel entrance when lit by daylight can make objects within the entrance more difficult to see than if there was no glare (e.g., at night) (*1*, *2*). This can significantly decrease the detection distance for hazards in the tunnel entrance. The second issue is related to the first in that large differences in illumination between the tunnel entrance and surrounding zones can cause the entrance to be perceived as a "black hole." This can cause drivers to decelerate quickly or drive erratically and generally poses a safety risk (*3*). The third issue is visual adaptation, which occurs when drivers transition from the high light levels outside the tunnel to dimmer interior tunnel lighting (*4*). Drivers' sensitivity to low-visual-contrast hazards is generally reduced until their eyes are able to adapt to the lower light levels, leading to a corresponding decrease in detection distance. In most cases, drivers' eyes have sufficient time to make this adjustment before entering the tunnel. This issue, however, may require special consideration if posted speeds are high, which gives drivers less time to adapt to lower lighting conditions.

Design Issues

Vehicle speed approaching the tunnel is an important consideration. Since drivers are assumed to be adapting to lower light levels as they approach the tunnel entrance, their travel speed affects the amount of time their eyes have to adjust to tunnel entrance illumination. At higher speeds, drivers will have less time to adjust (e.g., 13 s vs. 6.5 s for 40 and 80 km/h posted speeds, respectively), and significantly higher levels of tunnel illumination will be required to maintain adequate visibility (*1*). Consequently, if posted speeds approaching the tunnel are changed, then lighting requirements should be formally reexamined.

The sky is a significant source of daytime luminance, and the amount of sky in drivers' field of view during the approach to a tunnel entrance can lead to an elevated adaptation level prior to entering the tunnel (*1*). The topography of the area surrounding the tunnel often affects the amount of sky that is visible, with flat topographies exposing large regions of sky and therefore substantial luminances in the field of view, which elevates adaptation level. In general, the more sky that is visible in the field of view prior to tunnel entry, the higher the surface luminance that is required in the tunnel entrance in order to maintain adequate visibility. Greater surface luminance is also required when large, bright surfaces surround the tunnel entrance (e.g., large retaining walls, rocks, and other highly reflective surfaces).

Tunnel lighting requirements can be defined with regard to a common visual task (e.g., *2*). Specifically, this involves the detection of a hazard in the middle of the driver's lane and requires that drivers be able to stop before reaching the hazard. In the CIE calculations for determining lighting requirements, the target is assumed to have a height and width of 20 cm and a reflectivity of 20%. The ray between the driver eye point (assumed to be 1.5 m above the roadway) and a low hazard on the road is the basis for computing the effect of the luminance of peripheral visual zones on driver visibility and adaptation.

Counterbeam lighting appears to be more effective in making potential hazards easier to see because it increases the object's contrast relative to the background (*3*). The IESNA guidelines (*1*) suggest that lighting requirements can be reduced if counterbeam lighting is used in the transition zone.

Regardless of the type of lighting configuration, AASHTO (5) recommends that the lighting should be as continuous as possible to minimize the stroboscopic effect produced by the spacing of the luminaries. When driving at the design speed, frequencies of 5 to 10 cycles per second have been shown to cause eye annoyance.

Cross References

Countermeasures for Mitigating Headlamp Glare, 21-2
Characteristics of Effective Lighting at Intersections, 21-12

Key References

1. Illuminating Engineering Society of North America (IESNA) (2005). *IESNA Recommended Practice for Tunnel Lighting.* ANSI/IES RP-22. New York.
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5. AASHTO (2005). *Roadway Lighting Design Guide.* Washington, DC.

COUNTERMEASURES FOR IMPROVING PEDESTRIAN CONSPICUITY AT CROSSWALKS

Introduction

Countermeasures for improving pedestrian conspicuity at crosswalks refers to treatments that use flashing lights and beacons at midblock and intersection crosswalks. These lighting treatments do not necessarily improve visibility of pedestrians; rather, they are used to alert drivers to the presence of pedestrians in the crosswalk. The MUTCD (*1*) provides standards for implementing in-pavement flashing lights, sight-mounted flashing beacons, and flashing LEDs mounted in pedestrian crossing signs (in-sign flashing lights). This guideline provides additional information for the effective use of these countermeasures.

Design Guidelines

In-Sign Flashing Lights and Sign-Mounted Flashing Beacons (see examples below)

- Use either of these treatments to augment pavement markings and signs at uncontrolled crosswalks with heavy pedestrian and vehicle traffic, or that may not otherwise be clearly visible.
- Combine either of these treatments with in-pavement flashing lights to maximize drivers' awareness of pedestrian presence in the crosswalk. In-sign flashing lights should be coordinated to flash in synchronization with the in-pavement flashers.

In-Pavement Flashing Lights

- To promote pedestrian safety, consider using yellow in-pavement flashing lights at uncontrolled crosswalks, in locations (e.g., midblock) where drivers are not expecting a crosswalk, or when there are many other features in the surrounding environment that compete for drivers' attention.
- Use only in marked crosswalks. Also, include applicable warning signs (e.g., yield/stop for pedestrians) to further enhance the effectiveness of the treatment.
- It is suggested that in-pavement flashing lights be used when traffic volumes are between 5,000 and 30,000 vehicles per day and/or a minimum of 100 pedestrians per day (*8*).
- In-pavement flashing lights should be active (flashing) only when a pedestrian is present as determined by either a pedestrian pushing a button or by sensors that detect pedestrians' presence.
- Automated detection of pedestrians is preferred over manual pushbutton to activate the flashing lights.
- If automated detection is used, the sensing technology should minimize the occurrence of false and missed detections.
- Flashers that protrude above the pavement surface should be located so that they do not pose a safety hazard to bicyclists.

EXAMPLES OF IN-PAVEMENT FLASHING LIGHTS, IN-SIGN FLASHING LIGHTS, AND SIGN-MOUNTED FLASHING BEACONS

In-pavement flashing lights (*2*)

In-sign flashing lights (*3*)

Photo on left provided by authors

Sign-mounted flashing beacons (*4*)

Discussion

In-pavement flashing lights, sign-mounted flashing beacons, and flashing LEDs mounted in "Pedestrian Crossing" warning signs (in-sign flashing lights) have been shown to improve the safety at pedestrian crosswalks. These treatments are designed to alert drivers to the presence of pedestrians in the crosswalks or to make the crosswalk itself more conspicuous. When these treatments are used to supplement signs and markings at crosswalks, they have been shown to reduce the number of evasive conflicts between drivers and pedestrians (*4*), increase the rate of motorists' yielding to pedestrians (*4*, *5*), increase the distance at which drivers apply their brakes (*5*), reduce motorists' approach speed (*6*), and increase pedestrians' perception of safety (*7*) in both day and nighttime driving.

In-pavement flashing lights can be an attractive alternative to full signalization when the conditions are appropriate. The greatest improvements in safety generally occur in crosswalks with high pedestrian usage on roads with high average daily traffic. One source (*8*) recommends that in-pavement flashing lights be used when at least 100 pedestrians per day use the crosswalk and when average daily traffic (ADT) is between 5,000 and 30,000 vehicles per day. In-pavement systems, however, can be expensive to acquire, install, and maintain relative to other treatments. Consequently some jurisdictions (e.g., *9*) recommend that in-pavement flashing lights be used only when more traditional treatments prove unsuccessful at sufficiently improving safety. In-sign flashing LEDs or sign-mounted flashing beacons may provide successful, lower cost alternatives to in-pavement flashing lights for crosswalks with lower ADT or pedestrian density.

Dramatic improvements in driver behavior near crosswalks have been demonstrated when sign-mounted flashing beacons or in-sign flashing lights are used in combination with in-pavement flashing lights. In one study (*3*) almost 90% of vehicles yielded to pedestrians when in-pavement flashers and sign-mounted beacons were both present, 70% yielded with in-sign flashers only, and 18-25% yielded when there was no treatment. Similarly, another study (*6*) showed marked reductions in vehicle speed, pedestrian wait time, curb-to-curb duration of crossing, and disregarding pedestrians in the crosswalk when in-pavement flashing lights were used in concert with sign-mounted flashing beacons.

Design Issues

To differentiate between an empty crosswalk and one with pedestrians present, in-pavement flashing lights should be active only when pedestrians are present in the crosswalk (*1*). Drivers who are repeatedly exposed to continually flashing lights may become accustomed to them and eventually ignore them, particularly if the crosswalk is usually empty when they encounter it. Flashing lights can be activated either manually by pressing a pushbutton that indicates intent to cross, or automatically using sensors (passive detection) at the crosswalk entrances. Passive detection is generally preferred over using a manual pushbutton because some pedestrians may not bother to press a pushbutton before crossing or they may be confused by the pushbutton because there is no corresponding signal indicating when to walk (*8*). However, this confusion can be mitigated by including signage to indicate the purpose of the pushbutton (e.g., "Press button for crosswalk warning lights"; *3*).

Because in-pavement flashing lights protrude above the street surface, they can present a potential safety hazard to bicyclists (*5*). Careful placement of the markers where bicyclists (or motorcyclists) are not likely to ride and minimizing the height of protrusion should reduce this hazard.

Cross References

Characteristics of Lighting that Enhance Pedestrian Visibility, 21-10
Methods to Increase Driver Yielding at Uncontrolled Crosswalks, 15-2

Key References

1. FHWA. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
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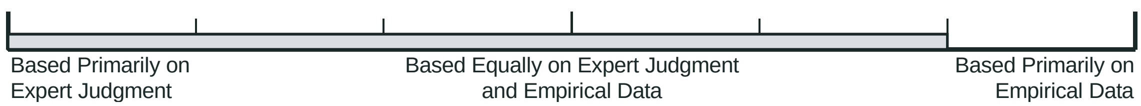
CHARACTERISTICS OF LIGHTING THAT ENHANCE PEDESTRIAN VISIBILITY

Introduction

This guideline addresses *characteristics of luminaires* at midblock and intersection crosswalks as well as for general street lighting that will enhance the visibility of pedestrians in or near the roadway. Factors that affect visibility under street lighting include intensity and color spectrum of the light source; reflectivity and color of the pedestrian clothing; reflectivity of the road surface; and whether the pedestrian is seen with peripheral or foveal vision. The characteristics addressed in this guideline include spectral power distribution (color) of the light source and luminaire location. Intensity of the light is an important characteristic that is covered in "Characteristics of Effective Lighting at Intersections" on page 21-12.

Design Guidelines

- Consider using luminaires with broad spectrum characteristics to promote longer detection distances and better recognition of pedestrians wearing a variety of clothing colors.
- Lighting a crosswalk with lamps of a color spectrum that differs from the overall road lighting can improve motorists' brightness perception, concentration, and search behavior through the crossing area.
- Luminaires should be located such that pedestrians in the crosswalk are seen in positive contrast. This can be accomplished by placing luminaires 10 to 15 feet ahead of a crosswalk in each direction of vehicle travel.
- Luminaires placed ahead of the crosswalk should include a sharp cutoff that minimizes exposure of glare to oncoming vehicles.



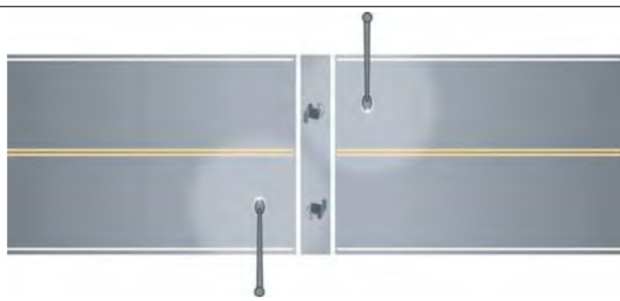

LPS (*1*)

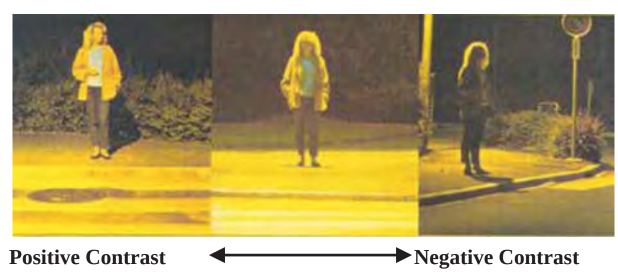

HPS (*2*)


LED (*2*)


Induction (*3*)

Examples of the color accuracy of objects illuminated by low pressure sodium (LPS), high pressure sodium (HPS), LED, and induction street lamps. In general, luminaires with broad spectrum characteristics (e.g., LED, induction, flourescent, and metal halide) yield better visibility, color discriminability, and viewer acceptance compared to narrow spectrum lights (e.g., LPS and HPS).


Placing luminaires 10 to 15 feet ahead of the crosswalk increases contrast by providing vertical illuminance (*4*).



Pedestrians are more visible when seen in positive contrast than in negative contrast (*5*).

Discussion

The issues associated with visibility of pedestrians at night under street lighting are complex. Drivers must detect pedestrians under mesopic lighting levels, at which both the rod and cone receptors in the retina support vision (*6*). The peak sensitivity of the cones occurs in the yellow region of the spectrum, while the rod peak sensitivity is near the blue/green. In mesopic lighting, visual sensitivity is shifted toward the blue/green portion of the visible spectrum compared to vision under photopic (daytime) lighting, when the cones are the primary visual receptors. However, pedestrian detection often relies on peripheral vision, which is dominated by the rods, causing even further bias toward the blue. Consequently, the spectral power distribution (SPD) of the light source can have a considerable effect on the visibility of a pedestrian depending on clothing color and position relative to the driver's forward gaze. Clothing that is similar in color to the lighting source is more highly visible than clothing of a contrasting color (e.g., under yellow light, a yellow shirt will appear to be brighter than a blue shirt will). This suggests that a broad spectrum light source will likely promote superior visibility for pedestrians wearing a variety of colors.

Various lamp technologies exhibit different spectral characteristics: metal halide (MH) lamps cast a bluish light, while high- and low-pressure sodium lamps are biased toward the yellow portion of the spectrum. The SPD of the light source has been shown to affect pedestrian visibility. In one study (*7*), detection distances were similar for pedestrians wearing white clothing under both HPS and MH lamp sources. However, detection distances were greater with MH lamps than with HPS lamps when pedestrians were wearing denim. White fabric reflects all colors somewhat equally, so it is less sensitive than blue denim to spectral bias in the light source. In contrast, denim reflects the blue light of the MH lamps while it absorbs much of the yellow from an HPS lamp. Newer technologies, such as LED, fluorescent, and induction lamps, are likely to result in better visibility over a broader range of clothing colors because these lamps generally can be designed to have broad spectral distributions. One study (*8*) demonstrated that detection distances were longer when using several LED and induction lamp systems compared to a lower wattage HPS lamp even though the HPS illuminance was greater than any of the alternative lamp types.

Color contrast can also play a role in improving visibility. Lighting a crosswalk with lamps of a color spectrum that differs from the overall road lighting can draw attention to the crosswalk and improve motorists' brightness perception, concentration, and search behavior through the crossing area (*9*).

Design Issues

Pedestrians are more visible in positive contrast (i.e., the background is darker than the pedestrian) than they are in negative contrast (i.e., the background is lighter than the pedestrian) (*5*). Luminaires placed 10 to 15 ft ahead of a crosswalk can improve contrast by providing vertical illuminance incident on the pedestrian that is stronger than the horizontal illuminance incident on the pavement behind the pedestrian (*10*, *11*). Bollard-mounted lights can also provide high-contrast vertical luminance at a crosswalk. In a lighting simulation (*10*), bollard-mounted luminaires were effective for providing superior vertical illumination for visibility of pedestrians, but they also were found to be more glaring than more traditional illumination methods. Regardless of the luminaire type, the system should be carefully designed to minimize drivers' exposure to glare from the luminaire.

Cross References

Characteristics of Effective Lighting at Intersections, 21-12

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CHARACTERISTICS OF EFFECTIVE LIGHTING AT INTERSECTIONS

Introduction

Characteristics of effective lighting at intersections refers to lighting characteristics that facilitate visibility at intersections while avoiding detrimental effects of glare from luminaires. Although vehicle headlamps provide some measure of illumination, additional fixed lighting is often required to provide light levels and contrast that are satisfactory for safe visibility at intersections. This guideline provides principles for improving visibility of pedestrians, vehicles, roadway features, and obstacles at intersections.

Design Guidelines

- Use a pole height, luminaire type, and luminaire cutoff pattern that will ensure adequate coverage of illuminance and uniformity of the light (see table below) throughout the intersection without exposing drivers to direct glare from the luminaire.
- Use the illuminance levels in the table below at intersections of continuously lighted streets with R2 or R3 pavement classifications. If lighting on an intersecting roadway is greater than the recommended value, the intersection illuminance should be increased proportionally.
- Use the alternative lighting layout in Figure B in areas with high pedestrian traffic (*1*, *2*).
- A partial lighting system can be utilized if the intersecting streets are not continuously lighted (*1*).

RECOMMENDED ILLUMINANCE FOR INTERSECTIONS

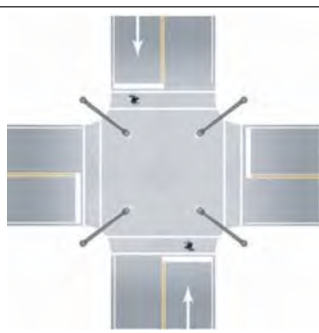
Functional Classification	Average Maintained Illumination at Pavement by Pedestrian Area Classification (Lux / fc)			Uniformity E_{avg}/E_{min}
	High	Medium	Low	
Major/Major	34.0 / 3.4	26.0 / 2.6	18.0 / 1.8	3.0
Major/Collector	29.0 / 2.9	22.0 / 2.2	15.0 / 1.5	3.0
Major/Local	26.0 / 2.6	20.0 / 2.0	13.0 / 1.3	3.0
Collector/Collector	24.0 / 2.4	18.0 / 1.8	12.0 / 1.2	4.0
Collector/Local	21.0 / 2.1	16.0 / 1.6	10.0 / 1.0	4.0
Local/Local	18.0 / 1.8	14.0 / 1.4	8.0 / 0.8	6.0

Source: IESNA (*1*)

Based Primarily on Expert Judgment

Based Equally on Expert Judgment and Empirical Data

Based Primarily on Empirical Data



A. Traditional layout – Good for illuminating conflict areas in the intersection, but poorer for visibility of pedestrians.

B. Alternative layout – Better for visibility of pedestrians, but harder to illuminate conflict areas in the intersection.

Source: Gibbons, Edwards, Williams and Andersen (*2*)

Discussion

A minimum level of illumination is required in the driving environment for drivers to visually detect pedestrians, obstructions, intersection features, and other vehicles in order to safely cross or turn at an intersection at night. Although vehicle headlamps provide some measure of illumination, additional fixed lighting is often required to provide light levels and contrast that are satisfactory for safe visibility at intersections. Most sources agree that the addition of illumination at an intersection increases visibility and enhances safety (e.g., *3*, *4*, *5*), and studies have shown that in some rural intersections as few as one or two luminaires can provide safety benefits (*3*, *6*). Luminaries are relatively expensive to install and maintain, however, and warranting criteria for the installation of lighting vary widely between jurisdictions. Nonetheless, well-designed lighting at critical intersections can be cost effective when considering the cost of crashes against the operating costs of the lighting. In one study (*7*), it was estimated that the payback for the addition of lighting would occur within as little as one year using HPS lighting (although HPS is not the lighting source preferred by drivers, visibility is still likely to be better with HPS than with no lighting). One methodological approach (*8*) for warranting illumination of isolated rural intersections is based on geometric, operational, environmental, and collision factors and uses ratings and weights to assess if full or partial illumination is warranted. The critical factors determining the need for illumination are traffic volumes, nighttime collisions attributable to lack of lighting, and the extent of raised channelization.

Design Issues

Three methods are described in the RP-8-00 standards (*1*) for the measurement and specification of light levels from roadway luminaires: (a) the luminance method, (b) the illuminance method, and (c) the small target visibility method. Each of these methods has advantages and disadvantages. The luminance method measures the light reflected from the road surface to the driver's eye. This method is preferred by some jurisdictions (e.g., *9*) for measuring tangent sections because it directly measures the light that the eye sees. However, the luminance method is impractical for use at intersections because the elevated lighting levels at the intersection skew the average luminance value used in the veiling luminance calculations (*9*). Likewise, the small target visibility method requires veiling luminance calculations to determine adaptation luminance. The illuminance method is suitable for designing lighting at intersections because it measures the amount of light incident on the roadway surface and is therefore independent of the observer and road reflectance properties.

The luminaire mast height, in combination with the beam pattern of the light source, affects the coverage, uniformity, and intensity of the illuminance measured at the pavement. Higher mast heights generally provide better coverage (e.g., more uniformity over a larger area) but at the expense of intensity. The results of a simulated lighting study (*10*) suggest that, to optimize lighting levels and coverage, a preferred lighting configuration includes luminaires with 50-foot mast heights. These luminaires should be mounted as close as possible to both intersecting centerlines in the intersection without entering into any clear zone. However, one disadvantage of a taller mast is the increased opportunity for exposing drivers to glare. Luminaire and geometric characteristics (e.g., luminaire cutoff pattern, vertical curvature approaching the intersection, etc.) should be considered when designing both the mast height and the lighting in general.

Cross References

Characteristics of Lighting that Enhance Pedestrian Visibility, 21-10

Key References

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PART V

Additional Information

CHAPTER 22

Tutorials

Tutorial 1: Real-World Driver Behavior Versus Design Models

Much of the information on sight distance presented in Chapter 5 reflects the application of empirically derived models to determine sight distance requirements. Such models, while valuable for estimating driver behavior across a broad range of drivers, conditions, and situations, have limitations.

This tutorial discusses how driver behavior as represented in sight distance models may differ from actual driver behavior. The design models presented in Chapter 5 use simplified concepts of how the driver thinks and acts. This simplification should not be viewed as a flaw or error in the sight distance equations. These models are a very effective way of bringing human factors data into design equations in a manner that makes them accessible and usable. After all, the intent of a sight distance equation is not to reflect the complexities of human behavior but to bring what we know about it into highway design in a concise, practical way. However, like any behavioral model, models for deriving sight distance requirements are not precise predictors of every case and there may be some limitations to their generality. Therefore, having an understanding of certain basic principles of human behavior in driving situations is useful to better interpret these models and to understand how they may differ from the range of real-world driving situations.

Sight distance formulas for various maneuvers (presented in Chapter 5) differ from one another, but they share a common simple behavioral model as part of the process. The model assumes that some time is required for drivers to perceive and react to a situation or condition requiring a particular driving maneuver (i.e., PRT), which is followed by some time (i.e., MT) and/or distance required to execute the maneuver. Sight distance equations for some maneuvers may contain additional elements or assumptions; however, all have this basic two-stage model somewhere at their core.

The two equations that follow show two versions of the general, two-component model. In both versions, the first term shows the distance traveled during the PRT component and the second term shows the distance traveled during the MT component. The difference is that the first equation shows a case where the distance traveled while executing the maneuver is based on the ***time*** required to make that maneuver (for example, the time to cross an intersection from a Stop), while the second equation shows a case where the distance traveled while executing the maneuver is based directly on the ***distance*** required to complete the maneuver (for example, braking distance for an emergency stop). For both forms of this general equation, vehicle speed (V) influences the second (MT) component.

The general form of the sight distance equation is:

$$d_{SD} = kVt_{prt} + kVt_{man}\text{, where maneuver time is input or}$$

$$d_{SD} = kVt_{prt} + d_{manV}\text{, where maneuver time is input}$$

Where:

d = required sight distance
V = velocity of the vehicle(s)
t_{prt} = PRT
t_{man} = MT
d_{manV} = distance required to execute a maneuver at velocity V
k = a constant to convert the solution to the desired units (feet, meters)

This model shows that the sight distance requirement is composed of (at least) two distances: there is a distance traveled while the driver perceives and evaluates a situation (determined by PRT and vehicle speed) and a distance traveled while executing the maneuver (determined by maneuver time/distance and vehicle speed). Figure 22-1 depicts the activities and sequence of activities associated with this simple model. As the figure shows, the PRT component is itself viewed as a series of steps. These individual steps are not explicit in the design equation but are included in the assumptions that underlie the PRT value. Design equations and their assumptions for specific maneuvers were discussed in Chapter 5. The sequential model of driver behavior shown in Figure 22-1 is a shared common conceptual underpinning of various sight distance equations.

However, in some respects, we can consider this model to be a "convenient fiction," in part because it depicts a simple, fixed, linear, and mechanistic process. While the model provides a useful basis for deriving approximate quantitative values for design requirements that work for many situations, real-world driving behavior is far more complex than the model suggests. While highway designers and traffic engineers are often required to work with less complex (i.e., imperfect) models of human visual perception, attention, information processing, and motivation, it is important that they understand those factors that may affect the application of design sight distance models for specific situations. Such an understanding will help them to prevent, recognize, or deal with sight distance issues that may arise. For a particular situation, the standard sight distance design equation might either underestimate or overestimate the actual needs of a driver. Subsequent sections of this tutorial deal with specific factors that affect the driver response and provide guidance for working with them. Before these specific factors are considered, it will be useful to have an appreciation of how the simple driver models that underlie sight distance requirements contrast with the real complexities of driver behavior.

There are a number of factors or conditions associated with driver responses to a hazardous event or object that are not reflected in the basic sight distance model, but nonetheless can have a profound effect on driver behavior and overall roadway safety:

- Conditions or events that occur prior to a hazardous event/object becoming visible to the driver
- How and when the driver processes relevant information
- Driving as an "episodic" activity versus driving as a "smooth and continuous" activity
- The nature of the hazardous object or event
- The nature of the driver's response
- Individual differences across drivers
- The quality and applicability of the empirical research used to develop the driver models

Each of these is discussed in more detail below.

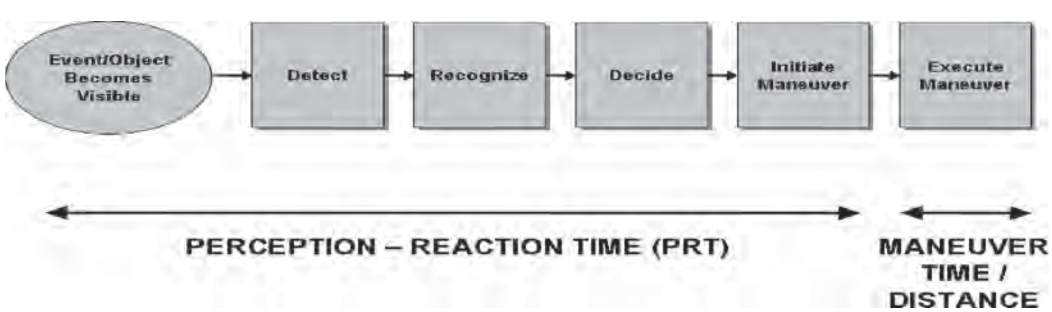

Figure 22-1. Diagrammatic version of the basic sight distance model.

Conditions or Events that Occur Prior to a Hazardous Event/Object Becoming Visible to the Driver

The model shown in Figure 22-1 is not sensitive to events that happen prior to the moment that the hazardous object or event becomes visible to the driver. In reality, the driver's ability to react to a hazardous object or event may be strongly influenced by previously occurring conditions or events. For example, drivers traveling on a roadway with few access points and little traffic may be unprepared to stop for a slow-moving vehicle ahead. In contrast, if drivers had been encountering numerous commercial driveways and intersections, with entering truck traffic, they might more readily react. Roadway design and operational features in advance of a hazardous event/object becoming visible are potentially important influences on behavior that are not explicit in the basic sight distance model. Figure 22-2 shows an expansion of the basic model, with added "driver state" factors (e.g., anticipation, situational awareness, caution, and locus of attention) that increase or decrease the driver's cognition preparation for a hazardous condition or event.

In Figure 22-2, an addition component to the model is shown prior to the event becoming visible. One element of the additional component is ***cognitive preparation.*** This general term encompasses the various active mental activities that can influence response times and decisions, such as driver expectancies, situational awareness, a general sense of caution, and where attention is being directed by the driver. Part II: Bringing Road User Capabilities into Highway Design and Traffic Engineering Practice provides some further explanation of these factors. As the arrows in the figure show, the driver's cognitive preparation as he or she encounters a hazardous object or event can influence the speed of detection, the speed and accuracy of recognizing the situation, and the speed and type of decision made about how to respond. The critical point is that the PRT associated with a particular hazardous object or event is influenced by the conditions or events preceding the driver's perception of the hazardous object or event.

The second element in the additional component in Figure 22-2 that occurs prior to the driver's perception of the hazardous object or event is ***speed selection.*** As discussed earlier, speed can have perceptual effects, influencing how easily a target object is detected or how accurately gaps are judged. Speed may affect the driver's sense of urgency, which can influence what maneuver options are considered and their relative appeal. Speed also may directly affect the difficulty, as well as the required time or distance, of the maneuver. Therefore, the driver's speed choice prior to the event may influence the driver's decision process; it may also influence the time available for the driver's response.

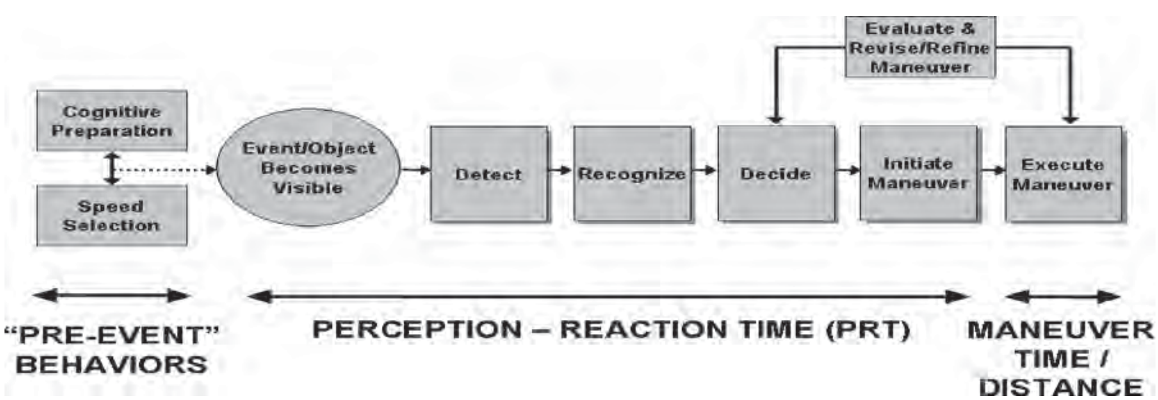

Figure 22-2. Added elements to basic sight distance behavioral model.

The basic sight distance behavioral model (Figure 22-1) makes assumptions about driver cognitive state and speed choice as the hazardous event is encountered. In reality, the driver does not arrive at the situation as a "blank slate." The locus of a sight distance problem, or its solution, therefore may turn out to be in advance of the problem site itself.

How and When the Driver Processes Relevant Information

The basic sight distance model shows a chain of mental and physical events taking place in the following sequential fashion:

1. A hazardous object or event becomes visible.
2. The presence of this object or event is detected by the driver.
3. The object or event is recognized and understood by the driver.
4. The driver makes a decision about what maneuver is needed to avoid or respond to the object or event.
5. The maneuver is initiated.
6. Once initiated, the maneuver is fully executed.

Each event in this chain takes some amount of time to occur, and—according to the basic model—one step does not begin until the previous step is complete. This assumed "serial processing" model is indeed one way a driver might respond, but it may not be typical. For example, if a driver sees some vague object ahead of the vehicle that might or might not be in the roadway, he or she may begin to brake even before the object is fully recognized. Also, once the object is fully recognized, the maneuver may be reconsidered (e.g., stopped, slowed, accelerated, or otherwise revised). Contrary to the serial processing assumed by the basic model, the mental processes shown by the various boxes in Figure 22-1 may actually occur in parallel, in a different sequence, or with modifications (feedback loops) as the process progresses. The assumed linear response sequence is therefore really a simplified case used for design purposes. It should not be viewed as a universal or invariant representation of the more complex perceptual and cognitive activity in complex driving situations.

Importantly, consistency in geometric design is required in order to meet driver expectations and to avoid surprising the driver.

Driving as an "Episodic" Activity versus Driving as a "Smooth and Continuous" Activity

Related to the previous point, the basic sight distance model reflects an "episodic" perspective of real-world driving. That is, some object or event becomes visible, and some driver maneuver(s) in response to the object or event are initiated and executed. Then, another object or event becomes visible, and another maneuver takes place. Real-world driving however, is normally smooth and continuous; it is not a jerky sequence of separate, individual episodes. Yet for ease of analysis, we often break driver behavior into individual events each requiring their own separate response, or we treat the roadway as a succession of discrete segments or zones. To the driver, though, the roadway and the driving task are generally smooth and continuous. Real drivers do not just react to events that randomly occur; they plan and predict and manage and adapt to events as they go along. Adopting an "episodic" perspective is useful for developing models of driver behavior that are both simple and reasonably predictive. A "smooth and continuous" perspective of real-world driving is much more difficult to model and quantify, especially in a manner that will easily generate a simple design parameter. From a human factors perspective, sight distance models are based on a little bit of driver performance data that describe how a driver *might* react, but may not reflect how drivers always or even typically behave. The use and application of the simpler sight distance model is generally reasonable from a design perspective, however, because it is somewhat conservative. Specifically, those drivers who encounter a situation without planning or anticipation are those most likely to be in need of the full sight distance requirement.

The Nature of the Hazardous Object or Event

For each sight distance design application, the analysis is based around some object, event, or roadway feature to which the driver must respond with a driving maneuver. That object, event, or roadway feature might be debris in the roadway, braking by a vehicle ahead, an approaching vehicle on a conflicting path, a freeway lane drop, a change in signal phase, a pedestrian entering the road, a railroad gate, an animal, a vehicle entering from a driveway, or many other things. The PRT process begins with the potentially hazardous object or event (the "visual target") becoming visible to the driver followed by some time to visually detect and recognize that target. Design equations have to include some estimate of when a target becomes visible and how long driver reaction will take. The many examples of potential hazards suggest just how different these may be as visual targets; therefore, making a single assumption is an obvious simplification. A target object may be large or small, bright or dull, familiar or unfamiliar, moving or stationary, or have other attributes that affect the driver's ability to accurately and quickly detect and recognize it. Explicitly or implicitly, design equations have to make some assumption about the characteristics of the visual target. Furthermore, visibility conditions may vary with weather, glare, light condition, roadway lighting, and intervening traffic (especially truck traffic). Again, design equations must be based on some assumption about visibility conditions.

A PRT model requires the user to be able to specify the point in time or space that the hazard becomes visible to the driver. However, this too may be an oversimplification. For example, there is usually no sharp threshold where an object in the road suddenly goes from being invisible to visible. Most hazards do not occur all at once, but evolve over some time, such as a vehicle moving into a lane in front of a driver. Some events might have a preview, such as a vehicle positioned in a driveway prior to its pulling out or children playing near the road prior to entering the road. Some events might have multiple cues; for example, a freeway lane drop has an initial taper, lane markings, and the point where the lane finally disappears. Sometimes the important visual target is not the hazard object or event itself but a cue about the hazard; for example, brake lights on a vehicle ahead may be a warning cue about a sudden severe deceleration, but they may also reflect a minor tap on the brake. Drivers cannot respond to the brake light in the same way they respond to recognition of the actual deceleration.

Overall then, the driver's response to a hazardous event or object will reflect specific physical characteristics, visibility conditions, and the evolving nature of the hazard itself.

The Nature of the Driver's Response

The behavioral components of sight distance models are based around some very specific maneuver in response to the object/event, with fixed assumptions about response parameters. For example, when responding to an unexpected need to stop, AASHTO (2004) assumes a braking maneuver with a deceleration of 3.4 m/s^2 (11.2 ft/s^2). Braking may be a reasonable response to assume, and 3.4 m/s^2 may be a reasonable deceleration to assume, but this certainly does not mean that braking at this level is always the driver's response to an unexpected hazard. The maneuver time and maneuver distance components of sight distance models are in many cases based on good empirical research and human factors considerations and work well for most applications. Still, the use of a single standard value is a convenient simplification. Actual maneuvers can be influenced by various factors. The perceived urgency of the situation (based on available time/

distance, driver/vehicle capabilities) determines options and shapes the way drivers respond, and often multiple options are available to the driver. For example, for an unanticipated stop, a driver may brake severely, or brake gradually and steer around, or swerve sharply. The surrounding physical, traffic, and social environment will affect these options: is there a lane or shoulder to steer around, are there adjacent or following vehicles, is the obstacle a piece of debris or a child, is there a passenger in the vehicle? Drivers also make trade-offs between speed versus control when executing maneuvers. The AASHTO deceleration value of 3.4 m/s^2 represents an estimate of a "comfortable deceleration" with which almost all drivers can maintain good vehicle control. In this sense it is appropriate for general design, but does not necessarily describe what drivers can do or actually do under all conditions or circumstances. Furthermore, once a driver initially selects and begins to execute a particular maneuver, the maneuver is not simply executed in a fixed manner. As Figure 22-2 illustrates, the situation is monitored and the maneuver is re-evaluated as it is being executed. The response may be refined or modified as it progresses. Drivers may not respond to a situation with a maximum response (e.g., maximum braking or steering), but may initiate a more controlled action and monitor the situation before committing to a more extreme action. For instance, they may begin gradual braking and check their mirrors for following traffic before decelerating more sharply or swerving.

Individual Differences Across Drivers

The diverse driving population ranges widely in capabilities and behaviors. Drivers vary in experience, visual acuity, contrast sensitivity, useful field of view, eye height, information processing rate, tolerance for deceleration, physical strength, and other factors related to PRT and MT. A design equation will typically be based around a design driver with some assumed set of attributes. To be conservative, the assumptions do not usually represent a typical driver, but rather reflect less capable drivers (e.g., 15th percentile in terms of some attribute). Assumptions are made about the state of the driver as well. For example, data are generally based on drivers who are sober and alert. Yet impaired or fatigued drivers may represent a large part of the crash risk. Alcohol, drugs, medication, and fatigue can have dramatic effects on the psychological processes that underlie PRT and MT. Driver distraction by activity within the vehicle is also a common occurrence that is not reflected in the design model. In-vehicle technologies, such as cell phones, navigation systems, and infotainment systems, are increasingly common. The multitasking driver is an increasing concern, but PRT models do not reflect this possibility.

The Quality and Applicability of the Empirical Research Used to Develop the Driver Models

The values used in design equations may or may not be derived from good empirical sources. In some cases (e.g., brake reaction time), there are numerous empirical studies and reasonably good agreement among them. In other cases, empirical data are very limited, are of lesser quality, or are only weakly applicable to the design issue in question. The quality and applicability of the numbers that come from empirical studies are sometimes questionable on a number of grounds: the sample of drivers may be small or unrepresentative; the situations evaluated may be limited and may not generalize well; the research may be out of date (given changes in roadways, traffic, vehicles, traffic control devices, and driver norms); the research setting (test track, simulator, laboratory) may lack validity; and results may conflict with results from other studies. It would be wrong to assume that sight distance design equations are necessarily based on a strong, high-quality empirical foundation that readily generalizes to all cases.

Another concern related to data quality and applicability is the inability of general design equations based on simple behavioral models to incorporate site-specific considerations. Empirical observations made at the site may be at variance with the predicted behaviors. Even when design equations are based on “good” data, the generality of the models suggests that credence should be given to any empirical data that can be collected at the site itself.

In summary, sight distance requirements are based on a highly simplified and mechanistic model of driver behavior and capabilities. This approach is reasonable and generally successful. The general assumptions often work well enough to approximate the needs of most drivers; however, it is important to recognize that this simple model has a number of limitations as a description of actual driver performance. When difficult sight distance problems are being diagnosed or addressed, it may be useful for the highway designer or traffic engineer to recognize how design models simplify driver actions and to acknowledge the realities of more complex driver perception and behavior.

Tutorial 2: Diagnosing Sight Distance Problems and Other Design Deficiencies

Introduction

The previous sections of this document—especially Chapter 5—have provided design guidelines for human factors aspects of various sight distance concepts. However, for users to implement these guidelines in a practical sense, it is desirable to provide a procedure for their operational application. Therefore, this section comprises a hands-on tool whereby practitioners can apply human factors techniques to analyze sight distance problems and other design deficiencies at a selected highway location.

A starting point for development of the current procedure was a review of previously documented procedures for conducting on-site driving task analyses (Alexander & Lunenfeld, 2001) that applied techniques such as commentary drive-thru procedures to generate checklist subjective-scaled ratings of hazard severity and information load. The current in-situ sight distance diagnostic procedure includes application of previously available engineering tools, e.g., AASHTO (2004) analyses of geometric requirements and MUTCD (FHWA, 2003) traffic control device requirements, and augments these techniques with those sight distance concepts presented in Chapter 5 of this HFG.

This sight distance diagnostic procedure consists of a systematic on-site investigation technique to evaluate the highway environment to support the concepts of interest, i.e., SSD, PSD, ISD, and DSD. The highway location is surveyed, diagrammed, and divided into component sections based on specific driving demands (e.g., requirement to perform a maneuver). Then each section is analyzed in terms of its suitability to support the required task (e.g., information provided to driver and allotted time to the complete required task). This procedure enables the practitioner to compare the *available* sight distance with the *required* sight distance to safely perform the driving task.

The Six-Step Procedure

The procedure consists of the following six steps:

1. Collect field data to describe roadway characteristics and other environmental factors affecting sight distance requirements and driver perception of a potential hazard.
2. Conduct engineering analyses applying traditional techniques, e.g., AASHTO design criteria and MUTCD compliance, to initially assess site characteristics or deficiencies.
3. Examine crash data and prepare collision diagram to seek possible association between safety and a sight distance problem.
4. Establish component roadway sections in which drivers respond to specific visual cues in order to initiate a maneuver to avoid a hazard.
5. Analyze driving task requirements (PRT and MT) and determine the adequacy of each component roadway section to support these requirements.
6. Develop engineering strategies for improvement of sight distance deficiencies.

A flow diagram overview of the process is shown in Figure 22-3. Following the description of the six-step procedure, an example application is provided.

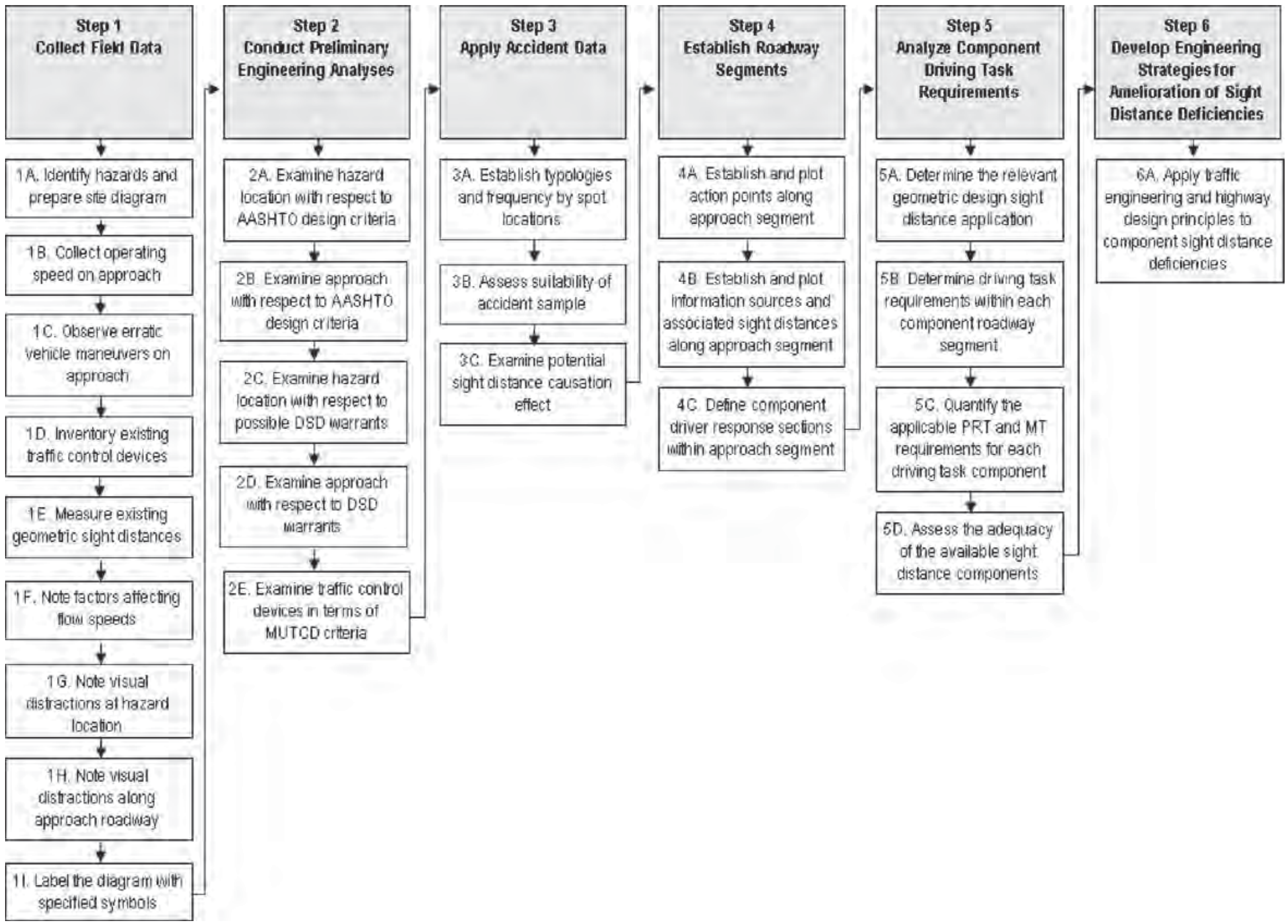

Figure 22-3. Flow diagram of six-step diagnostic process.

Step 1: Collect Field Data

This step involves making specific field measurements and observations. Data are to be gathered both at the location of the designated hazard as well as the approach roadway section immediately in advance of the hazard. Approach distances over which field measurements should be gathered are determined from Table 22-1 at the end of this step. Approach distances were derived from approximated perception-reaction and sign reading times applied to the designated operating speeds.

Step 1A: Identify Hazard and Prepare Site Diagram

Procedure	Product/Application
The specific hazard location under investigation is identified and the approach roadway is diagrammed. Example of hazards requiring sight distance consideration and the associated sight distance concepts are as follows. • A hidden intersection (SSD) • An exit from a shopping mall in a heavily lit (e.g., visually cluttered) setting (DSD) • A vehicle approaching an intersection (ISD) • An oncoming vehicle in a passing zone (PSD) Note distances from hazard to the following features: (1) traffic control devices, (2) intersecting driveway or roadways, and (3) sight distance obstructions.	***References:*** Lunenfeld, H., and Alexander, G. J. (1990). *A User's Guide to Positive Guidance* (FHWA-SA-90-017). Washington, DC: FHWA.

Step 1B: Collect Operating Speed on Approach

Procedure	Product/Application
Spot speeds for randomly selected vehicles are to be observed at a sufficient advance distance upstream from the hazard beyond which slowing in response to the hazard is expected. Candidate speed collection techniques are radar/laser detection, automated speed recorders, and manual timing. References noted in the column to the right describe appropriate procedures to ensure random vehicle selection and suitable sample sizes. In the event that the approach roadway section is characterized by horizontal or vertical curvature, speed collection points should be selected so as to represent operational speeds at these locations.	The product of this step will be a statistical distribution of speeds from which means and/or percentile values will be applied to estimate vehicle speed for the approach roadway under study. ***References:*** Hanscom, F. R. (1987). Validation of a non-automated speed data collection methodology. *Transportation Research Record, 1111,* 54–61. Robertson, H. D. (Ed.). (2000) *Manual of Transportation Engineering Studies,* Washington, DC: Institute of Transportation Engineers.

Step 1C: Observe Erratic Vehicle Maneuvers on Approach

Procedure	Product/Application
Observations of vehicle movements should be considered in situations of sufficiently high traffic volumes to justify this type of study, e.g., 100 vehicles per hour (vph) and above. Typical target vehicle behaviors indicative of a sight distance problem are sudden slowing (e.g., observable break light activation) and abrupt lane changes when these maneuvers are not induced by other vehicles in the traffic stream. A considerable literature base is available regarding the conduct and interpretation of "traffic conflicts" studies; however, the reader is cautioned that traffic conflicts studies are limited to interactions between vehicles. A sight distance–induced erratic maneuver, on the other hand, can involve a single vehicle. Methodological literature addressing conflicts study is helpful with respect to observational techniques.	The outcome of this step should be insightful with respect to possible sight distance–induced vehicle behaviors. ***References:*** Parker, M. R., and Zegeer, C. V. (1989). *Traffic Conflict Techniques for Safety and Operations* (FHWA-IP-88-026 (*Engineer's Guide*) and FHWA-IP-88-027 (*Observer's Guide*)). Washington, DC: FHWA. Taylor, J. I., and Thompson, H. T. (1977). *Identification of Hazardous Locations: A Users Manual* (FHWA-RD-77-82). Washington, DC: FHWA.

Step 1D: Inventory Existing Traffic Control Devices

Procedure	Product/Application
Document existing signs, signals, and pavement markings along with their respective distances from the hazard under study. Document the age of these signs, signals, and markings, as well. The letter heights and mounting heights of signs need to be recorded. Document any visual obstructions.	The resulting device inventory will be subsequently applied in this diagnostic analysis to evaluate the suitability of provided information, as well as visual distractions and information processing demands on motorists as they approach the hazard under study.

Step 1E: Measure Existing Geometric Sight Distances

Procedure	Product/Application
Existing geometric sight distance limitations along the approach to the hazard must be measured in accordance with AASHTO criteria. Specifically, sight distance observations should be made from an elevation above the pavement that equals the design driver eye height (i.e., 3.5 ft) to a point ahead that is 2.0 ft above the pavement.	This step will yield the length of specific roadway subsections along the approach in which drivers must observe and process available information (e.g., roadway features and other vehicles). ***References:*** AASHTO (2011). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.

Step 1F: Note Factors Affecting Flow Speeds

Procedure	Product/Application
Certain roadway environmental features are known to affect drivers' selection of speed. Examples are pavement defects, narrow shoulder widths and protruding bridge piers, abutments, guardrails, median barriers, etc.	Documentation and general awareness of these factors are important because subsequent minor highway improvement projects may result in higher highway speeds, thus producing increased sight distance requirements.

Step 1G: Note Visual Distractions at Hazard Location

Procedure	Product/Application
Certain environmental conditions are known to produce "visual clutter" (i.e., distractions that make hazards more difficult for drivers to perceive). Examples include (1) off-roadway lighting, (2) commercial signing in driver field of view, (3) complex urban intersection designs, (4) high volumes of vehicular/pedestrian movement (including bicycles), and (5) proliferation of intersection traffic control devices. Observations should document drivers' field of view at SSD from hazard (e.g., AASHTO (2011)).	This inventory of visual distractions will be subsequently applied in a human factors analysis to determine the applicable sight distance criterion (e.g., DSD, to address driver perception and information-processing time requirements at the hazard location). ***References:*** AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 1H: Note Visual Distractions Along Approach Roadway

Procedure	Product/Application
As in Step 1G, visual environmental conditions along the approach to the hazard also may produce driver distractions. These need to be included in the field data collection process. Observations should document drivers' field of view at DSD from hazard (e.g., AASHTO (2011)).	This inventory of visual distractions will be subsequently applied in a human factors analysis to determine the applicable sight distance criterion to address driver information-processing time requirements on the approach to the hazard location. ***References:*** AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 1I: Label the Diagram with Specified Symbols

Procedure	Product/Application
SD_{HAZ}—*Sight distance to a potential hazard.* The point at which a location or object is first detectable to an approaching motorist. **A**—*Point of required action.* The location where an intended maneuver (e.g., hazard avoidance) is to be completed. **SD_{TCD}**—*Sight distance to a traffic control device.* The point at which the device is first detectable to an approaching motorist. **TCD**—*Traffic control device.* The location of the device that warns of the hazard, measured as a distance from the location or object about which information is provided.	The inclusion of uniform symbols on the site diagram will facilitate the subsequent sight distance analysis (see Figure 22-4).

Table 22-1. Recommended approach distance to hazard for collection of field data.

Estimated Operational Speed (mi/h)	Approach Distance to Hazard (ft)		
	Visually Cluttered Environment	Visually Non-Cluttered Environment	Additional, when TCDs Present
25	360	180	95
30	440	220	110
40	580	290	150
50	730	370	185
60	880	440	220
70	1030	520	260

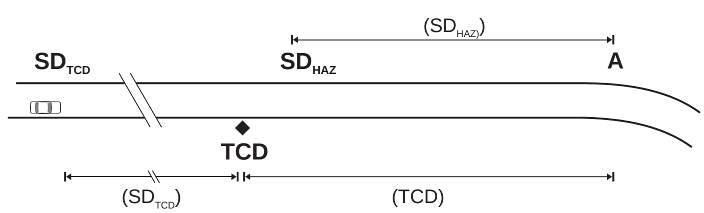

Figure 22-4. Example symbol diagram: A two-lane 55-mi/h roadway approaches a 35-mi/h curve.

Step 2: Conduct Preliminary Engineering Analyses

This step involves the application of traditional traffic engineering techniques (e.g., AASHTO Design Policy geometric design criteria and DSD warrant) as a preliminary determinant of site deficiencies. In addition, the placement of traffic control devices needs to be examined in terms of MUTCD requirements.

Step 2A: Examine Hazard Location with Respect to AASHTO Design Criteria

Procedure	Product/Application
To ensure a valid engineering diagnosis of sight distance to a hazard, it is necessary to first assess whether the hazard location itself has any inherent design shortcomings. One geometric deficiency potentially associated with a hazard location might be roadside that fails to meet requirements of the AASHTO *Roadside Design Guide.* Other examples are (1) a high-crash intersection may be deficient with respect to existing corner sight distance (AASHTO, 2011) and (2) in the case of a high incidence of run-off-road crashes, observed operational speeds (from Step 1A above) may differ significantly from the design speed upon which the curve radius and super elevation of the curve under consideration were based (AASHTO, 2011).	The resulting analytical steps ensure that the hazard location itself is free of any inherent design shortcomings that have the potential for confounding the intended sight distance diagnosis. ***References:*** AASHTO (2002). *Roadside Design Guide.* Washington, DC. AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 2B: Examine Approach with Respect to AASHTO Design Criteria

Procedure	Product/Application
As with the procedure noted in Step 2A, to ensure the integrity of the overall sight distance diagnosis, it is necessary to assess whether the approach to the hazard location has any inherent design shortcomings. (For example, a substandard lateral clearance to a roadside object along the approach may create a visual obstruction, thus producing an unintended sight distance limitation.) Likewise, crest vertical sight distances along the approach should be consistent with observed operational speeds gathered during Step 1B.	The resulting analytical steps ensure that the approach to the hazard is free of any inherent design shortcomings that have the potential for confounding the intended sight distance diagnosis.

Step 2C: Examine Hazard Location with Respect to Possible DSD Warrants

Procedure	Product/Application
AASHTO (2011) (e.g., section on DSD) notes a distinction between typical stopping sight distances and those in which drivers are required to make complex decisions (i.e., in which drivers require PRT beyond the design value [which is typically 2.5 s]). The DSD criterion applies to a difficult-to-perceive information source in a roadway environment that may be visually cluttered. Therefore, the hazard location needs to be examined for conditions of "visual noise" from competing sources of information (e.g., roadway elements, traffic, TCDs, and advertising signs). Specific sources of visual clutter were also noted in Step 1E.	When DSD-warranting conditions are found to exist, apply the sight distance requirements noted in AASHTO (2011), rather than conventional stopping distances based on a 2.5-s PRT. ***References:*** AASHTO (2011). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 2D: Examine Approach with respect to DSD Warrants

Procedure	Product/Application
The approach to the hazard location also must be examined for conditions of visual clutter meeting requirements for DSD application. In particular, these conditions could take the form of roadside distractions and/or complex TCDs at intersections along the approach.	Visual clutter along an approach to a hazard detracts from drivers' perception of the hazard. When DSD-warranting conditions are found to exist along an approach to a hazard, the distraction is sufficient such that available sight distance to the hazard must be restricted to that distance beyond the distraction.

Step 2E: Examine Traffic Control Devices with Respect to MUTCD Criteria

Procedure	Product/Application
The MUTCD (FHWA, 2009) prescribes device placement criteria for signs, signals, and markings. Devices at both the hazard location and along the approach need to be examined for MUTCD compliance. Note that the MUTCD establishes mandatory, recommended, and optional requirements for the application of TCDs. The examination conducted in this step (as well as Steps 4 and 5) should reflect these MUTCD criteria.	The output of this step will reveal whether inadequate traffic control device application (e.g., insufficient warning distance or inappropriate warning message) constitutes possible sources of driver confusion. Inappropriate or inadequate TCD information can result in longer information processing times, thereby creating an artificial sight distance problem. ***References:*** FHWA (2009). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.

Step 3: Apply Crash Data

This step involves the integration of traffic crash data into the analysis. The objective is to locate specific crash-prone locations within the roadway segment, which may be indicative of sight distance problems. The practitioner is cautioned that the absence of crashes does not rule out the existence of a sight distance problem, as crashes are probabilistic events and reporting requirements are variable.

Step 3A: Establish Typologies and Frequency by Spot Locations

Procedure	Product/Application
A review of crash data will reveal the occurrence of various types in close vicinity to the hazard under study. The associated pre-collision paths and their proximity to highway features may suggest the existence of a sight distance problem. Certain crash types are typically associated with specific sight distance problems: • Run-off-road, fixed-object crashes (SSD) • Side-swipe, rear-end crashes (PSD) • Right-angle, rear-end crashes (ISD)	A collision diagram is used to summarize crash types by location. For examples, see Robertson et al. (2000) and Hostetter and Lunenfeld (1982). ***References:*** Robertson, H. D., Hummer, J. E., and Nelson, D. C. (Eds.) (2000). *Manual of Transportation Engineering Studies.* Washington, DC: ITE. Hostetter, R. S., and Lunenfeld, H. (1982). *Planning and Field Data Collection (FHWA-TO-80-2).* Washington, DC: FHWA.

Step 3B: Assess Suitability of Crash Sample

Procedure	Product/Application
While well-documented procedures exist to statistically establish crash causation (see Council et al. (1980)), this level of sophistication is not necessary for the diagnosis of a sight distance problem. It is desirable (to the extent possible based on available crash data) to establish causation inferences based on crash patterns and to rule out non-sight-distance causal effects.	A reasonable level of confidence (albeit logic-based rather than statistically rigorous) regarding crash causation is possible based on the following: • Inferences based on crash patterns rather than a single event • Occurrences whereby non-sight-distance factors can be logically ruled out. ***References:*** Council, F. M., Reinfurt, D. W., Campbell, B. J., Roediger, F. L., Carroll, C. L., Dutt, A. K., and Dunham, J. R. (1980). *Accident Research Manual* (FHWA-RD-80-016). Washington, DC: FHWA.

Step 3C: Examine Potential Sight Distance Causation Effect

Procedure	Product/Application
Certain patterns of crash behaviors (i.e., pre-collision maneuvers) are suggestive of sight distance problems: for example, single-vehicle or run-off-road crashes with a fixed object that may appear visible under some conditions but may not be easily detectable to drivers during conditions of more limited visibility (e.g., darkness). These patterns need to be examined to determine whether sight distance is a potential causal factor (i.e., adequate nighttime sight distance conveyed by TCDs).	A collision diagram can be descriptive of the location and nature of a sight distance hazard, thus supporting a hypothesis regarding the effect of a sight distance problem.

Step 4: Establish Roadway Segments

The practitioner specifies component roadway approach segments in a manner to support the detailed human factors analysis in Step 5. Separate approach roadway segments are theoretically required for driver PRT and hazard avoidance maneuver functions. The product of this section is a series of driver task diagrams that depict the point where driver actions are required to avoid a potential hazard, information sources that warn of the hazard, and drivers' available sight distances to perform the necessary information-processing and maneuver tasks.

Step 4A: Establish and Plot Action Points Along Approach Segment

Procedure	Product/Application
Specific locations within the study roadway section requiring a driver action (e.g., maneuver) will be identified and plotted. For example, the hazard under study is the key point where action (e.g., driving at the posted speed) is likely required. Where a maneuver (e.g., decelerating) is necessary prior to reaching the hazard, the "compliance point" is the point where the maneuver is initiated (e.g., start of the deceleration distance). In the event that the approach roadway section requires some intermediate action (e.g., merging from a dropped traffic lane), this action also needs to be identified and plotted. Action points on the site diagram prepared in Step 1 should be indicated on the diagram by the symbol **A.** A series of sequential action points may be designated as $\mathbf{A}_1$, $\mathbf{A}_2$, etc.	The developed site diagram will indicate specific points where vehicle actions are required. Examples are as follows: • Approach maneuver (such as slowing) as required by the hazard under study • Any intermediate actions (e.g., required lane change) on the approach to the hazard under study

Step 4B: Establish and Plot Information Sources and Associated Sight Distances Along Approach Segment

Procedure	Product/Application
Any driver action (e.g., hazard avoidance) must be based on information available to the driver. In this step, drivers' information sources that inform an intended action must be located and documented. Information to the driver should be available from (1) detection of the hazard and/or (2) traffic control devices pertaining to the hazard. The following information/detection sources were noted on the site diagram in Step 1I: • Initial point of sight distance to the hazard identified by the symbol $\mathbf{SD_{HAZ}}$ • Location of TCD providing information regarding the hazard identified by the symbol **TCD** • Initial point of sight distance to the applicable TCD identified by the symbol $\mathbf{SD_{TCD}}$ In this step, separate plots of component information-processing segments may be helpful.	The developed site diagram will indicate specific points where information pertaining to the hazard is available to the driver. Examples are as follows: • Point of initial detection opportunity on an approaching of both the hazard and any traffic control device warning of the hazard. • Specific locations of any TCDs advising of the hazard. NOTE: In the event that the hazard under study is not detectable (i.e., defined in the visual field), the symbol $\mathbf{SD_{HAZ}}$ would not appear on the diagram. In such instances the required sight distance to action point (**A**) will be determined in Step 5.

Step 4C: Define Component Driver Response Sections Within Approach Segment

Procedure	Product/Application
Distinctly different driver information-processing tasks are associated with each detection and maneuver activity. In this step, roadway sections will be designated and plotted to illustrate the required travel distances over which the driver would perform these varied information-processing and maneuver tasks. Depending upon physical characteristics of the roadway section under study, four distinct driver response cases are possible: **Case 1:** Direct line of sight to hazard $\mathbf{SD_{HAZ} \rightarrow A}$ **Case 2:** Intervening traffic control device (i.e., warning of hazard) $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$ **Case 3:** Intervening (e.g., distracting) hazard ($\mathbf{A_2}$) within sight line of first hazard ($\mathbf{A_1}$) $\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ **Case 4:** Intervening traffic control device and distracting hazard $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$	The product of this step is a diagrammed set of roadway component sections, each corresponding to specific information-processing and maneuver driver tasks. The distance over which a driver can react to a detectable hazard is the roadway section $\mathbf{SD_{HAZ} \rightarrow A}$. In this roadway section, the driver would detect the hazard and perform any required preparatory maneuver (e.g., decelerating). Likewise, the distance over which a driver reacts to an advance traffic control device is the roadway section $\mathbf{SD_{TCD} \rightarrow TCD}$. In this roadway section, the driver has the opportunity to detect the sign and comprehend the sign's message. The message becomes readable at the point $\mathbf{LD_{TCD}}$ (i.e., the legibility distance from the sign), which will be computed and located during Step 5. In the final approach section to the hazard, $\mathbf{TCD \rightarrow A}$, the driver would complete the decision-making and maneuver tasks.

Step 5: Analyze Component Driving Task Requirements

In this step, the practitioner applies human factors principles (comprising information-processing and decision-making criteria) to ensure the adequacy (or to quantify the shortcoming) of the approach roadway to allow for time/distance hazard avoidance requirements.

Step 5A: Determine the Relevant Geometric Design Sight Distance Application

Procedure	Product/Application
The analysis of driving task requirements involves application of the appropriate sight distance value for the given task. Sight distance requirements (to accommodate both the information-processing and maneuver tasks) approaching action points (**A**) will fall into one of the following categories (depending upon roadway environment condition), which were identified in Section 5.2: • Stopping sight distance (SSD) • Intersection sight distance (ISD) • Decision sight distance (DSD) • Passing sight distance (PSD)	The result of this task is the specification of the applicable procedure (e.g., engineering design formula) for the computation of $\mathbf{SD_{HAZ}}$ corresponding to each identified hazard or action point. The required sight distance based on application of the appropriate design formula is applied to determine the required length of the roadway segment under study.

Step 5B: Determine Driving Task Requirements Within Each Component Roadway Segment

Procedure Driver information-processing demands vary as a function of environmental factors, according to the four cases indicated below. Identify separate PRT and MT components of the driving task for each of the four cases. Specific values of PRT and MT will be determined subsequently.	
Case 1: Direct line of sight to hazard; no traffic control $\mathbf{SD_{HAZ} \rightarrow A}$ In this case, PRT and MT are determined from Section 5.2. **Case 2:** Intervening traffic control device (i.e., warning of hazard) $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$ 1. Driver must detect traffic control device: $\mathbf{SD_{TCD} \rightarrow LD_{TCD}}$ 2. Driver must read or otherwise comprehend message and may begin decision process: $\mathbf{LD_{TCD} \rightarrow TCD}$ (Legibility distance will be determined in Step 5C.) 3. Decision and maneuver must be completed: $\mathbf{TCD \rightarrow A}$	**Case 3:** Intervening, distracting hazard at $\mathbf{A_2}$ within sight line of first hazard at $\mathbf{A_1}$ $\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ 1. Driver requires longer PRT due to complex visual scene ahead: $\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A}$ Consider DSD application. 2. Driver may require longer MT due to complexity of maneuver and visual scene: $\mathbf{SD_{HAZ2} \rightarrow A_2 \rightarrow A}$ **Case 4:** Intervening traffic control device and distracting hazard at A_2 within sight line of first hazard A_1 $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ 1. Driver must detect traffic control device: $\mathbf{SD_{TCD} \rightarrow LD_{TCD}}$ 2. Driver must read or otherwise comprehend message and may begin decision process: $\mathbf{LD_{TCD} \rightarrow TCD}$ 3. Driver may require longer MT due to complexity of maneuver and visual scene: $\mathbf{SD_{HAZ2} \rightarrow A_2 \rightarrow A}$

Step 5C: Quantify the Applicable PRT and MT Requirements for Each Driving Task Component

Procedure

The general model to be applied for quantifying driver task requirements (i.e., required PRT and MT) is $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$. Driver task requirements are determined for each task as follows.

No TCDs present:

$\mathbf{SD_{HAZ} \rightarrow A}$

Apply applicable PRT and MT requirement corresponding to predetermined condition (i.e., SSD, ISD, DSD, or PSD as determined in Step 5A).

TCDs present:

$\mathbf{SD_{TCD} \rightarrow LD_{TCD}}$

Drivers should be able to detect a TCD prior to time required to comprehend its message; 2.5 s is desirable, although less time may be adequate (e.g., second, third, etc. in a sequence).

$\mathbf{LD_{TCD} \rightarrow TCD}$

$\mathbf{LD_{TCD}}$ is the "legibility distance" or approach distance at which a traffic control device message is comprehended. A detailed discussion in the following paragraphs addresses the $\mathbf{LD_{TCD}}$ for signs. In the case of pavement markings, $\mathbf{LD_{TCD}}$ is the advance distance at which the marking is visually recognized.

The $\mathbf{LD_{TCD}}$ for a sign is the distance at which its legend is read or its symbol message is comprehended. PRT requirements for signs consist of reading times for the message legend and symbol as follows (Smiley, 2000):

$$\textit{Reading Time} = 1^*(\text{number of symbols}) + 0.5^*(\text{number of words and numbers})\ [\text{s}]$$

The minimum reading time is 1 s. For messages exceeding four words, the sign requires multiple glances; the driver must look back to the road and at the sign again. Therefore, for every additional four words and numbers, or every two symbols, an additional 0.75 s should be added to the reading time.

TCDs present (continued):

This segment must be sufficient in length to accommodate the reading time noted above. However, its length is constrained by letter height (i.e., limited to 40 ft for every inch of letter height). For example, a 4-in. letter-height sign must be read within a distance of $4 \times 40 = 160$ ft. On a 40 mi/h (58.8 ft/s) roadway, the driver is limited to a maximum of 160/58.8 or 2.7 s to read the sign. Moreover, the traffic engineer must consider that the driver can not be expected to fixate on the sign.

Considering the driver's alerted state after reading the sign, *decision time* (i.e., time to make a choice and initiate a maneuver if required) can range from 1 s for commonplace maneuvers (e.g., stop, reduce speed) to 2.5 s or more when confronted with a complex highway geometric situation.

$\mathbf{LD_{TCD} \rightarrow TCD \rightarrow A}$

While the required MT may be initiated prior to passing the TCD, it must be completed in the above-noted segment. MT values associated with designed sight distance considerations are treated in Chapter 5. Additional literature sources of extensive maneuver time data are available (Lerner, Steinberg, Huey, and Hanscom, 1999).

References:

Lerner, N. D., Steinberg, G. V., Huey, R. W., and Hanscom, F. R. (1999). *Understanding Driver Maneuver Errors, Final Report* (Contract DTFH61-96-C-00015). Washington, DC: FHWA.

Smiley, A. (2000). Sign design principles. *Ontario Traffic Manual.* Ottawa, Canada: Ontario Ministry of Transportation.

Step 5D: Assess the Adequacy of the Available Sight Distance Components

Procedure	
Case 1: Direct line of sight to hazard; no traffic control **$SD_{HAZ} \rightarrow A$** Does the subsection length **$SD_{HAZ} \rightarrow A$** allow sufficient time for the driver to perform any required hazard avoidance maneuver? **Case 2:** Intervening traffic control device (i.e., warning of hazard) **$SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A$** Does the subsection length, **$SD_{TCD} \rightarrow LD_{TCD}$** allow sufficient time (minimum 1.5 s) for the driver to detect the traffic control device? Does the subsection length, **$SD_{TCD} \rightarrow TCD$** allow sufficient time for the driver to detect and read the traffic control device? Does the subsection length, **$TCD \rightarrow A$** allow sufficient time for the driver to perform any required hazard avoidance maneuver?	**Case 3:** Intervening, distracting hazard at **A_2** within sight line of first hazard at **A_1**. **$SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1$** Does then subsection length **$SD_{HAZ1} \rightarrow A_1$** allow sufficient time for the driver to process and respond to the intervening distraction (i.e., apply DSD criteria) and perform any required hazard avoidance maneuver? **Case 4:** Intervening traffic control device and distracting hazard **A_2** within sight line of first hazard **A_1**. **$SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1$** Does the subsection length, **$SD_{TCD} \rightarrow LD_{TCD}$** allow sufficient time (2.5 s desirable; minimum 1.0 to 1.5 s) for the driver to detect the traffic control device? Does the subsection length, **$SD_{TCD} \rightarrow TCD$** allow sufficient time for the driver to detect and read the traffic control device? Does the subsection length, **$TCD \rightarrow A_1$** allow sufficient time for the driver to process and respond to the intervening distraction (i.e., apply DSD criteria) and perform any required hazard avoidance maneuver?

Step 6: Develop Engineering Strategies for Improvement of Sight Distance Deficiencies

In this final step, the practitioner recommends improvement (e.g., traffic control device applications or minor design modifications) to correct deficiencies.

Step 6A: Apply Traffic Engineering and Highway Design Principles to Component Sight Distance Deficiencies

Procedure	Product/Application
Case 1: Direct line of sight to hazard; no traffic control $\mathbf{SD_{HAZ} \rightarrow A}$ Available sight distance to hazard, $\mathbf{SD_{HAZ}}$, is less than required based on Step 5B results.	Add warning traffic control device, increasing warning distance as shown in Case 2 below.
Case 2: Intervening traffic control device (i.e., warning of hazard) $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$ Total available sight distance less than the required sight distance from Step 5C.	If $\mathbf{LD_{TCD} \rightarrow TCD}$ is inadequate (i.e., information overload): • Apply "information spreading" by adding more devices, each with less information • Increase legibility distance (e.g., by increasing letter size) If $\mathbf{LD_{TCD} \rightarrow TCD \rightarrow A}$ is inadequate: • Increase warning distance, $\mathbf{SD_{TCD} \rightarrow LD_{TCD}}$, via improving the TCD's legibility distance • Apply larger device, increase letter size • In DSD condition, add conspicuity device (e.g., flashing beacon) or consider ITS application. If $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD}$ is inadequate: • Reduce information load on existing TCDs • Apply additional TCDs (e.g., delineation devices, advance supplemental devices) to convey essential information.
Case 3: $\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ Available sight distance to hazard, $\mathbf{SD_{HAZ}}$, is less than required based on Step 5B results.	Add warning traffic control device, achieving increased warning distance.
Case 4: $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ Total available sight distance less than the required sight distance from Step 5C.	Apply combination of Case 2 solutions noted above.

Example Application: Sight Distance Diagnostic Procedure

The example driving situation consists of a 55-mi/h, two-lane rural roadway that approaches a 35-mi/h curve followed by a stop-controlled intersection. The intersection approach is to a main highway, which requires application of destination guide signing.

Driver requirements in this situation are as follows:

1. Reduce speed from 55 to 35 mi/h to negotiate curve
2. Process traffic control device information related to intersection (e.g., destination name sign)
3. Stop for intersection

Step 1: Collect Field Data and Prepare Site Diagram

The labeled site diagram is shown in Figure 22-5.

Step 2: Conduct Preliminary Engineering Analyses

This example requires a sight distance analysis to two separate potential hazards. The first is a 35-mi/h curve that requires slowing from 55 mi/h; and the second is an intersection that is heavily signed with a stop sign and two guide signs, containing multiple route shields, symbols, and destination names. The approach roadways to each hazard point are separately treated as follows: (1) curve approach and (2) signed intersection approach.

Curve Approach Segment

Steps 2A through 2D: Examine Site with Respect to AASHTO Design and DSD Criteria. For the purpose of this example, it is assumed that geometrics conform to AASHTO and that DSD criteria (e.g., visually cluttered environmental conditions) do not apply.

Step 2E: Examine Traffic Control Devices for Compliance with the MUTCD. The MUTCD specifies requirements for warning signs. The curve warning sign in the example is a "W1-2, Horizontal Alignment Sign" with a 35-mi/h advisory speed plate. Section 2C-05 of the MUTCD specifies an advance placement guideline for warning signs. Given the requirement to slow from 55 to 35 mi/h, the minimum recommended distance in Table 2C-4 (located on page 2C-5) is 138 ft (FHWA, 2003).

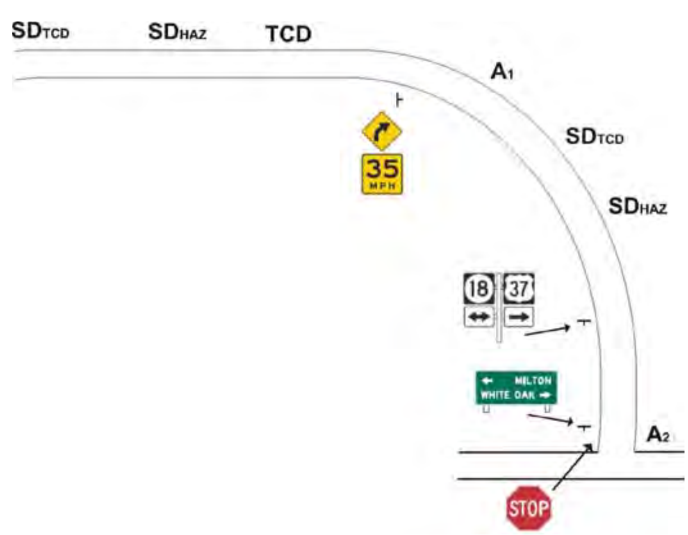

Figure 22-5. Example site diagram.

Signed Intersection Approach Segment

Steps 2A through 2D: Examine Site with Respect to AASHTO Design and DSD Criteria. For the purpose of this example, it is assumed that geometrics conform to AASHTO and that DSD criteria (e.g., visually cluttered environmental conditions) do not apply.

Step 2E: Examine Traffic Control Devices for Compliance with the MUTCD. This segment is a stop-controlled intersection approach containing signs to multiple routes and destinations.

The MUTCD provides requirements for guide signs on conventional roads. Signs in the example consist of a "directional assembly" with destination name signs and route shields. Required advance distances and spacing of these signs is given in Figure 2D-2 (FHWA, 2009). Typically, when a series of guide signs is placed sequentially along the approach to an intersection there is a 100- to 200-ft separation between the first two signs. The minimum spacing between signs is 100 ft, which is intended to enable drivers to read the entire message on both signs. Section 2D.06 requires 6-in. letter heights for a 35-mi/h roadway (FHWA, 2009).

Specifications for stop sign size and placement are contained in Chapter 2A of the MUTCD. As shown in Figure 2A-2, the stop sign should be set back a minimum of 12 ft from the intersection. The recommended letter height is 8 in. (FHWA, 2009).

Step 3: Apply Crash Data

Not conducted as part of this example.

Step 4: Establish Roadway Segments

This example requires a sight distance analysis to two separate potential hazards. The first is slowing from 55 mi/h to 35 mi/h, the posted curve advisory speed; and the second is a stop-controlled approach to an intersection containing signs to multiple routes and destinations. As above, the approach roadways are discussed separately.

Curve Approach Segment. The roadway segment requiring the driver to slow from 55 mi/h to 35-mi/h is labeled in accordance with Steps 4A and 4B and is shown below. The two sight distance driver response scenarios follow:

- **Case 1,** direct line of sight to hazard (i.e., 55-mi/h speed zone to 35-mi/h curve): $\mathbf{SD_{HAZ} \rightarrow A}$
- **Case 2,** intervening traffic control device (i.e., 35-mi/h advisory speed sign warning of hazard): $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$

This roadway is diagrammed in Figure 22-6.

Signed Intersection Approach Segment. On this roadway section, motorists traveling at 35-mi/h are confronted with a stop-controlled intersection and two guide signs containing destination names and route shields. Because sight distance to the intersection is limited by a curve on the approach, a sight distance analysis is critical. The component section diagram is labeled in accordance with Steps 4A and 4B and shown below. The sight distance driver response scenarios follow:

Figure 22-6. Curve approach segment diagram.

- **Case 1,** direct line of sight to hazard (i.e., 35-mi/h speed zone to intersection): $\mathbf{SD_{HAZ} \rightarrow A}$
- **Case 2:** Three intervening traffic control devices
  - A route shield assembly:
    $\mathbf{SD_{TCD1} \rightarrow LD_{TCD1} \rightarrow TCD_1 \rightarrow A}$
  - A destination name sign:
    $\mathbf{SD_{TCD2} \rightarrow LD_{TCD2} \rightarrow TCD_2 \rightarrow A}$
  - A stop sign:
    $\mathbf{SD_{TCD3} \rightarrow LD_{TCD3} \rightarrow TCD_3 \rightarrow A}$

This roadway segment is diagrammed in Figure 22-7.

Step 5: Analyze Component Driving Task Requirements

Curve Approach Segment. The roadway section, requiring the driver to slow from a 55-mi/h speed zone to a 35-mi/h curve, considers sight distance to the curve and legibility distance requirements posed by the advisory speed sign.

Step 5A: Determine the Relevant Design Sight Distance Application. The applicable design sight distance is *slowing sight distance*—the required distance for a driver to observe the curve ahead and adjust speed accordingly. In the event that certain visual noise conditions or other factors are present that would render the curve difficult to perceive, then the practitioner must consider applicable DSD criteria (discussed in Chapter 5). Where a traffic control device is present, driver information-processing time is required to observe and comprehend the sign as well as slow to a safe curve negotiation speed. In the current example (i.e., a rural uncluttered environment), DSD criteria are not applied.

Step 5B: Determine the Driving Task Requirements. Considering the two possibilities (i.e., Case 1 in which the driver observes the curve ahead without seeing the sign, and in Case 2 whereby the driver observes and comprehends the sign), the requirements for each are as follows:

- **Case 1,** direct line of sight to hazard (i.e., 55-mi/h speed zone to 35-mi/h curve):
  $\mathbf{SD_{HAZ} \rightarrow A}$
  The sight distance requirement in this case is simply that the driver observes the curve ahead and slows to a safe speed.
- **Case 2,** intervening traffic control device (i.e., 35-mi/h advisory speed sign warning of hazard):
  $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$
  The sight distance requirement in this case is that the driver observes the sign, comprehends the sign message, and slows to a safe speed.

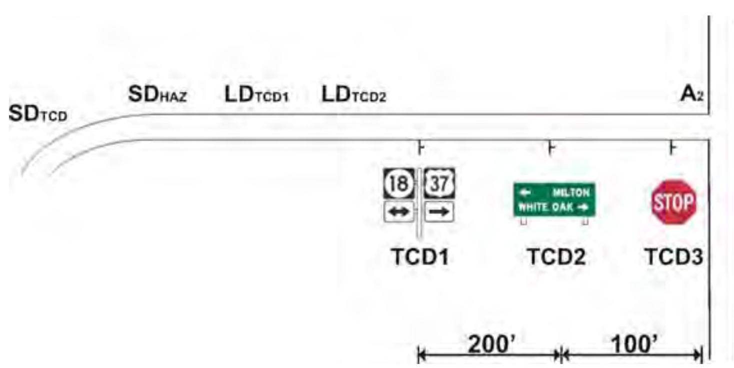

Figure 22-7. Intersection approach segment diagram.

Step 5C: Quantify the Applicable PRT and MT Requirements for Each Driving Task

- **Case 1,** direct line of sight to hazard (i.e., 55-mi/h speed zone to 35-mi/h curve):
  $\mathbf{SD_{HAZ} \rightarrow A}$

  Because DSD does not apply (determined previously), the design PRT value of 2.5 s is applied; thus the PRT component of sight distance is 202 ft (i.e., 2.5 s times 80.85 ft/s). The MT requirement (4.0 s) is derived from the need to slow from 55 mi/h to 35 mi/h at a comfortable deceleration level (i.e., .23*g*), which requires 261 ft. Thus the total PRT and MT sight distance requirement is 463 ft.

  The comfortable deceleration level is derived from Table 2-25 of AASHTO (2011). (For safety purposes, wet weather deceleration is considered.) However, AASHTO (2011) acknowledges that its deceleration data may be outdated and that more rapid (albeit uncomfortable) decelerations are common. A typical such deceleration is .35*g* (Knipling et al., 1993), resulting in an MT of 2.6 s. It is also known that most reasonably alert drivers are able to initiate braking within a PRT of 1.6 s (Chapter 5). Applying these performance parameters to slowing from 55 to 35 mi/h, the total required PRT distance is 129 ft plus 172 ft MT distance, or 301 ft.

  It is unlikely that the need to slow to 35 mi/h would be visually evident from an advance distance of either 301 or 463 ft. Therefore, the critical sight distance consideration is based on the application of the speed advisory sign.

- **Case 2,** intervening traffic control device (i.e., 35-mi/h advisory speed sign warning of hazard):
  $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$

  In this case the driver needs to detect the sign, read the sign, and decelerate to the safe curve speed. A critical requirement for sight in advance of a sign (i.e., allowing time to comprehend the sign's message) is known as *legibility distance.* There is a considerable body of knowledge regarding sign legibility distance requirements (Smiley, 2000).

  For simple warning signs, the MUTCD specifies an advance placement guideline, which includes "an appropriate legibility distance" of 175 ft for word legend signs or 100 ft for symbol signs. The MUTCD sign placement requirement to allow for slowing from 55 to 35 mi/h is 350 ft.

  Driver requirements imposed by the MUTCD rule in this case are as follows: Given that 2.0 s are needed to detect and comprehend (e.g., minimum 1.0 s for detection plus 1.0 s for symbol comprehension) the simple warning sign message prior to the initiation of slowing, the deceleration requirement would be .32 *g* or approximately the equivalent slowing rate of skidding on wet pavement. In this example the required PRT and MT distances would be 161 and 189 ft respectively, for a total of 350 ft.

  For signs with complex messages (i.e., sets of destination names or symbols in combination with symbols), message comprehension may require significantly more legibility distance. The next example illustrates such a situation.

Signed Intersection Approach Segment. On this roadway section, motorists traveling at 35 mi/h are confronted with a stop-controlled intersection and two guide signs containing destination names and route shields. Because sight distance to the intersection is limited by a curve on the approach, a sight distance analysis is critical.

Step 5A: Determine the Relevant Design Sight Distance Application. As the driver approaches a stop-controlled intersection, there must be sufficient available stopping sight distance (Chapter 5) to enable stopping at the stop line. (While negotiation of the intersection involves the application of intersection sight distance, the current example is limited to approaching the intersection.)

Step 5B: Determine the Driving Task Requirements. Considering the two possibilities (i.e., Case 1 in which the driver proceeds to the intersection ahead while ignoring the signs, and Case 2 whereby the driver observes and comprehends the intermediate signs), the requirements are as follows:

- **Case 1,** direct line of sight to hazard (i.e., 35-mi/h speed zone to intersection):
  $\mathbf{SD_{HAZ} \rightarrow A}$

  The sight distance requirement (to accommodate travel time) in this case is simply that the driver observes the intersection ahead and safely slows to a stop.
- **Case 2,** three intervening traffic control devices, i.e.:
  - A route shield assembly:
    $\mathbf{SD_{TCD1} \rightarrow LD_{TCD1} \rightarrow TCD_1 \rightarrow A}$
  - A destination name sign:
    $\mathbf{SD_{TCD2} \rightarrow LD_{TCD2} \rightarrow TCD_2 \rightarrow A}$
  - A stop sign:
    $\mathbf{SD_{TCD3} \rightarrow LD_{TCD3} \rightarrow TCD_3 \rightarrow A}$

  $\mathbf{TCD_1}$ is a route shield assembly bearing two route designations; $\mathbf{TCD_2}$ is a destination guide sign with two destination names and directional arrows; and $\mathbf{TCD_3}$ is a stop sign.

  The sight distance requirement in this case is that the driver detects and comprehends the signs and slows to a safe stop at the stop line.

Step 5C: Quantify the Applicable PRT and MT Requirements for Each Driving Task

- **Case 1,** direct line of sight to hazard (i.e., speed reduction from 35 mi/h to stop at the stop line):
  $\mathbf{SD_{HAZ} \rightarrow A}$

  The design *stopping sight distance* does not accommodate information-processing requirements of the intervening guide signs. The AASHTO design SSD value (AASHTO, 2004) for a 35-mi/h approach is the range of 225 to 250 ft, which accounts for both the PRT and MT tasks.

  However, this 225- to 250-ft sight distance would barely accommodate the physical placement of the two guide sign assemblies that are shown in the Figure 22-7. Moreover, the information-processing load imposed by the signs requires significant attention in terms of sight distance requirements. Therefore the Case 2 condition is treated below.

- **Case 2,** intervening traffic control device (i.e., guide signs):
  $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$

  The general model (above) entails the following considerations. First, there must be sufficient sight distance so that the sign is detected prior to the time required to comprehend the sign's message, thus application of the $\mathbf{SD_{TCD}}$ term. This advance distance is not specified in the MUTCD. Nevertheless, 2.5 s is desirable for this sign detection task, although less time may be adequate as motorists who are looking for signs are generally aware of the expected position in their field of view. The more essential approach sight distance to a traffic control device is that required to comprehend its message.

  $\mathbf{LD_{TCD}}$ refers to legibility distance—the approach distance at which a TCD legend is read or its symbol message is comprehended. The legibility distance of a legend sign is determined by multiplying a legibility index (i.e., the distance at which a given unit of letter height is readable) by the letter height. The applicable legibility index values are shown in Table 22-2. For example, the legibility distance typically associated with 6-in. letter height is 240 ft (40 times 6).

Table 22-2. Legibility index.

Metric	US Customary
4.8 meters/ centimeter of letter height	40 feet/ inch of letter height

The legibility distance of symbol signs has been researched in a laboratory study (Dewar, Kline, Schieber & Swanson, 1994) and found to significantly exceed that of legend signs (despite the high degree of variability in the study data). For example, the mean legibility distance for the right curve arrow symbol was determined to be 283 m (with a standard deviation of 68 m). Considering that a 55-mi/h approach allowing a 2.5-s advance sight distance and 1.0-s reading time would consume only 86 m, pure symbol signs are not expected to result in an information-processing problem.

The required PRT for this example roadway segment consists of three components: detecting the signs, comprehending the sign messages, and detecting the intersection. Each is separately discussed.

Sign Detection. Upon a driver's detection of the first sign, the second and third signs would require minimal detection time. The recommended detection time for the first sign is 2.5 s; however, the second two signs are likely to be detected much more rapidly. "Alerted" PRT responses are known to occur in as little as 1.0 to 1.5 s. Moreover, signs can be quickly detected as drivers know where to look for signs and typically scan toward expected sign locations. Therefore, a conservative sign detection PRT for the example roadway segment is (2.5 + 1.5 + 1.5) or 5.5 s.

Sign Comprehension. Sign comprehension consists of reading the sign plus making the resultant decision (e.g., right or left turn in response to the sign's information). The PRT requirement (Smiley, 2000) is based on sign-response reading and decision time, for which general rules are noted in Table 22-3.

Table 22-3. General rules for sign comprehension PRT requirements.

Comprehension Task	PRT Requirements
Reading	Time requirements for reading the sign are 0.5 s for each word or number, or 1 s per symbol, with 1 s as a minimum for total reading time. In the event of the sign's containing redundant information, the reading time computation should be limited to critical words. The suggested formula for estimating sign reading time is: Reading time = 1(number of symbols) + 0.5(number of words and numbers). For messages exceeding four words, the sign requires multiple glances, which means the driver must look back to the road and at the sign again. Therefore, for every additional four words and numbers, or every two symbols, an additional 0.75 s should be added to the reading time. When the driver is sufficiently close to see a sign at an angle, the sign is not visible for the last 0.5 s. Therefore, 0.5 s should be added to the required reading time. An exception applies to signs requiring a maneuver before the sign is reached, as no further reading is required.
Deciding	Considering the driver's alerted state having read the sign, decision time can range from 1 s for commonplace maneuvers (e.g., stop or reduce speed) to 2.5 s or more when confronted with a complex highway geometric situation.

The first guide sign assembly contains two numbers and two symbols, requiring 3.0 s of reading time; the second contains two designation names and two symbols, also requiring 3.0 s; and the third is a simple and familiar one-word regulatory sign, requiring 1 s. Thus the total sign reading time is 7.0 s. This estimate is highly conservative, as drivers would likely scan the guide signs seeking only a particular name or route number; however, it is necessary to provide sufficient information-processing sight as some drivers may need the entire set of information. An additional 3.0 s is considered for decision time responses to the three signs. Thus the total comprehension time for the three signs is 10 s.

Intersection Detection Distance. As noted above under the Case 1 ($\mathbf{SD_{HAZ} \rightarrow A}$) discussion, the stopping sight distance requirement considers a 2.5-s PRT.

A summary of the above-noted PRT requirements, if separately considered, is shown in Table 22-4. The sum of PRT requirements would apply to a serial task process. However, a realistic assessment of PRT requirements considers that many of the tasks in Table 22-4 are concurrent. For example, stop sign comprehension would not logically entail a separate process of perceiving the intersection, thus conceivably reducing the total PRT by 2.5 s. In addition, following a driver's 2.5-s detection of the initial sign, the subsequent two signs would likely be detected with a minimum detection time (e.g., 1.0 s rather than 1.5 s), thus conceivably reducing the total PRT by another 1.0 s. Therefore, subtracting 3.5 s from the serial total of 19.5 s, the estimated PRT requirement becomes 16.0 s.

The MT requirement (i.e., to slow from 35 mi/h to a stop at the specified AASHTO g-force) calculates to 4.7 s over a distance of 120 ft. The extent to which the deceleration process would occur concurrently with the various sign-response tasks is uncertain. However, it is logical (and best serves liability concerns) to allow time for comprehension of all signs prior to the initiation of the slowing response.

Therefore, the overall sight distance requirement is approximately 16.0 s of sign information processing at 35 mi/h (51.45 ft/s) or 823 ft, plus the 120-ft deceleration distance, for a total of 943 ft. (Actual requirements will reflect real-world conditions. If possible, data should be collected at the relevant sites.)

A final consideration is the necessity that drivers have sufficient time to comprehend a sign's message during the interval when the message is discernable. Therefore, an essential sight distance diagnostic step is to compare the available sign legibility distance (i.e., available reading distance) with distance traveled during reading PRT (i.e., required reading distance and decision time). Table 22-5 contrasts the distance traveled during PRT with the legibility distance. While the guide signs in this example accommodate both reading time and associated decision time, the decision component of PRT can obviously be accomplished after the driver passes the sign.

Table 22-4. Summary of PRT requirements.

Driving Task	PRT Requirement (s)
Perceive initial guide sign	2.5
Perceive next three signs @ 1.5 s/sign	4.5
Comprehend initial guide sign	4.0
Comprehend second guide sign	4.0
Comprehend stop sign	2.0
Perceive intersection	2.5
Total	**19.5**

Table 22-5. Contrast of distance traveled during PRT with legibility distance.

Sign	Legibility Distance (ft)	PRT Distance (ft)
1. 6-in. letters: 2 Numbers + 2 Symbols	240	231
2. 6-in. letters: 2 Numbers + 2 Symbols	240	231
3. 8-in. letters: 1 Word	320	51

Step 6: Develop Engineering Strategies for Improvement of Sight Distance Deficiencies

Not conducted as part of this example.

Tutorial 3: Detailed Task Analysis of Curve Driving

A task analysis of the different activities that drivers must conduct while approaching and driving through a single curve (with no other traffic present) was conducted to provide qualitative information about the various perceptual, cognitive, and psychomotor elements of curve driving. Consistent with established procedures for conducting task analyses (Campbell and Spiker, 1992; Richard, Campbell, and Brown, 2006; McCormick, 1979; Schraagen, Chipman, and Shalin, 2000), the task analysis was developed using a top-down approach that successively decomposed driving activities into segments, tasks and subtasks. The approach used in this tutorial was specifically based on the one described in Richard, Campbell, and Brown (2006); readers interested in additional details about the methodology should consult that reference (available at http://www.tfhrc.gov/safety/pubs/06033/).

The curve driving task was broken down into four primary segments, with each segment generally representing a related set of driving actions (see Figure 22-8). The demarcation into segments was primarily for convenience of analysis and presentation and does not imply that the curve driving task can be neatly carved up into discrete stages. Within each segment, the individual tasks that drivers should or must perform to safely navigate the curve were identified. Moreover, these driving tasks were further divided based on the information-processing elements (perceptual, cognitive, and psychomotor requirements) necessary to adequately perform each task. The perceptual requirements typically refer to the visual information about the curve and the surrounding roadway that drivers need to judge the curvature, determine lane position and heading, etc. The cognitive requirements typically refer to the evaluations, decisions, and judgments that drivers have to make about the curve or the driving situation. The psychomotor requirements refer to the control actions (e.g., steering wheel movements, foot movements to press brake, etc.) that drivers must make to maintain vehicle control or to facilitate other information acquisition activities.

The task analysis presented in Table 22-6 shows the driving tasks and corresponding information-processing subtasks associated with driving a typical horizontal curve, approaching from a long tangent. Drivers must also engage in other ongoing safety-related activities, such as scanning the environment for hazards; they may also engage in in-vehicle tasks such as adjusting the radio, using windshield wipers, or consulting a navigation system (just to name a few). However, these more generic tasks are not included in the task analysis in order to emphasize those tasks and subtasks that are directly related to curve driving.

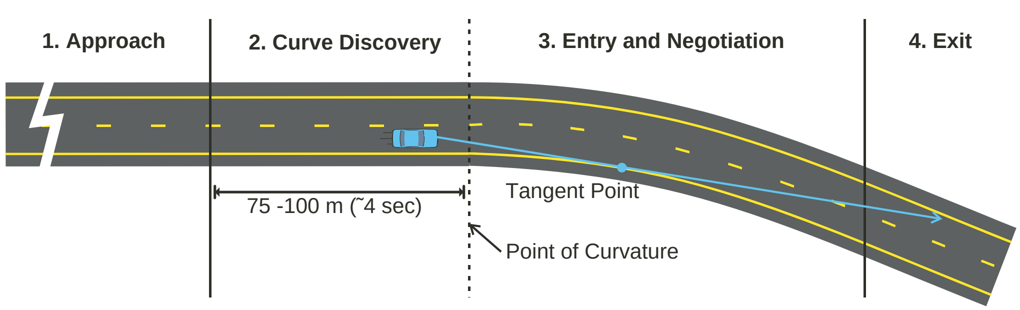

Figure 22-8. The four primary segments of the curve driving task.

Table 22-6. Driving tasks and information-processing subtasks associated with a typical curve.

Driving Task	Perceptual Requirements	Cognitive Requirements	Psychomotor Requirements
1. Approach			
1.1 Locate bend	Inspect forward roadway scene for evidence of bend	Recognize visual cues indicating departure from straight path	Eye movements needed for scanning
1.2 Get available speed information from signage	Visually scan environment for signage	Read and interpret sign information	Head and eye movements needed for scanning
1.3 Make initial speed adjustments	Look at speedometer	Read speedometer information and compare to posted speed	Execute necessary foot movements to achieve desired speed change
2. Curve Discovery			
2.1 Determine curvature	Look at roadway and environment features at curve location	Estimate curve angle based on visual image and experience	Head and eye movements needed for scanning
2.2 Assess roadway conditions (e.g., low friction, poor visibility)	Look at roadway in front of vehicle	Determine conditions requiring (additional) speed reductions	Execute necessary foot movements to achieve desired speed change
2.3 Make additional speed adjustments	Look at speedometer and/or view speed cues from environment	Read speedometer and/or judge safe speed based on cues and experience	Execute necessary foot movements to achieve desired speed change
2.4 Adjust vehicle path for curve entry	Look at roadway/lane marking information in the immediate forward view	Determine the amount of steering wheel displacement required to achieved desired lane position	Head and eye movements needed for viewing, and precise arm movements for steering control
3. Entry and Negotiation			
3.1 Adjust speed based on curvature/lateral acceleration	Perceive lateral acceleration and look at roadway motion cues	Judge safe speed based on visual cues and experience or read speedometer	Execute necessary foot movements to achieve desired speed change
3.2 Maintain proper trajectory	Look at tangent point or intended direction	Determine amount of steering wheel displacement required to achieved desired heading	Head and eye movements needed for scanning, and precise arm movements for steering control
3.3 Maintain safe lane position	Look at roadway/lane marking information in the immediate forward view	Determine amount of steering wheel displacement required to achieved desired lane position	Head and eye movements needed for viewing, and precise arm movements for steering control
4. Exit			
4.1 Accelerate to appropriate speed	Look at speedometer and/or view speed cues from environment	Read speedometer and/or judge safe speed based on cues and experience	Execute necessary foot movements to achieve desired speed change
4.2 Adjust lane position	Look several seconds ahead down the roadway	Determine amount of steering wheel displacement required to achieved desired heading	Head and eye movements needed for scanning, and precise arm movements for steering control

The primary source of information for segment tasks was the comprehensive driving task analysis conducted by McKnight and Adams (1970); however, other research more specifically related to curve driving were also used:

- Donges, E. (1978). Two-level model of driver steering behavior. *Human Factors, 20*(6), 691–707.
- Fitzpatrick, K., Wooldridge, M. D., Tsimhoni, O., Collins, J. M., Green, P., Bauer, K. M., Parma, K. D., Koppa, R., Harwood, D. W., Anderson, I., Krammes, R. A., and Poggioli, B. (2000). *Alternative Design Consistency Rating Methods for Two-Lane Rural Highways.* Final Report. (FHWA-RD-99-172). McLean, VA: FHWA.

- Groeger, J. A. (2000). *Understanding Driving: Applying Cognitive Psychology to a Complex Everyday Task.* Hove, U.K.: Psychology Press.
- Krammes, R. A., Brackett, R. Q., Shafer, M. A., Ottesen, J. L., Anderson, I. B., Fink, K. L., Collins, K. M., Pendleton, O. J., and Messer, C. J. (1995). *Horizontal Alignment Design Consistency for Rural Two-Lane Highways.* Final Report. (FHWA-RD-94-034). McLean, VA: FHWA.
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- Pendleton, O. J., and Messer, C. J. (1995). *Horizontal Alignment Design Consistency for Rural Two-Lane Highways.* Final Report. (FHWA-RD-94-034). McLean, VA: FHWA.
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- Salvendy, G. (Ed.). (1997) *Handbook of Human Factors and Ergonomics* (2nd ed.). New York: Wiley.
- Serafin, C. (1994). *Driver Eye Fixations on Rural Roads: Insight into Safe Driving Behavior.* (UMTRI-94-21). Ann Arbor: University of Michigan Transportation Research Institute.
- Underwood, G. (1998). *Eye Guidance in Reading and Scene Perception.* Oxford: Elsevier.
- Vaniotou, M. (1991). The perception of bend configuration. *Recherche Transports Securite,* (7), 39–48.

For the most part, these references and the other research provided information about which tasks were involved in a given segment, but not complete information about the specific information-processing subtasks. To determine this information, the details about the information-processing subtasks and any other necessary information were identified by the authors based on expert judgment and other more general sources of driving behavior and human factors research (e.g., Groegor, 2000; Salvendy, 1997; Underwood, 1998).

Tutorial 4: Determining Appropriate Clearance Intervals

Methods for determining appropriate clearance interval length vary from agency to agency, and there is no consensus on which is the best method. The Institute for Transportation Engineers recommends several procedures for determining clearance interval duration in a 1994 informational report (see ITE, 1994) on signal change interval lengths. These methods include:

1. A rule of thumb based on approach speed, such as this one presented in the ITE *Traffic Engineering Handbook* (Pline, 1999):
   – Yellow change time in seconds = operating speed in mi/h/10
   – Red clearance interval = 1 or 2 s
2. Formulas for calculating interval lengths based on site, vehicle, and human factors characteristics, such as this equation (from Pline, 1999):

   $$CP = t + \frac{V}{2a \pm 64.4g} + \frac{W + L}{V}$$

   Where:

   CP = non-dilemma change period (change + clearance intervals)
   t = perception-reaction time (nominally 1 s)
   V = approach speed, m/s [ft/s]
   g = percent grade (positive for upgrade, negative for downgrade)
   a = deceleration rate, m/s^2 (typical 3.1 m/s^2) [ft/s^2 (typical 10 ft/s^2)]
   W = width of intersection, curb to curb, m [ft]
   L = length of vehicle, m (typical 6 m) [ft (typical 20 ft)]

3. A uniform clearance interval length—Various studies report that uniform value of 4 or 4.5 s for the yellow change interval length throughout a jurisdiction is sufficient to accommodate most approach speeds and deceleration rates. Refer to *Determining Vehicle Signal Change and Clearance Intervals* (ITE, 1994) for more discussion on this.

The *Manual on Uniform Traffic Control Devices* (FHWA, 2007) states that a yellow change interval should be approximately 3 to 6 s, and the *Traffic Engineering Handbook* (Pline, 1999) states that a maximum of 5 s is typical for the yellow change interval. The red clearance interval, if used, should not exceed 6 s (FHWA, 2007), but 2 s or less is typical (Pline, 1999). The traffic laws in each state may vary from these suggested practices. ITE recommends that the yellow interval not exceed 5 s, so as not to encourage driver disrespect for signals.

Tutorial 5: Determining Appropriate Sign Placement and Letter Height Requirements

When determining the appropriate sign placement, it is important to consider a number of driver-related factors. The *Traffic Control Devices Handbook* (Pline, 2001) describes a process that utilizes these factors and is the basis for the steps described below. This method is mostly focused on guide and informational sign applications.

Step 1. Calculate the Reading Distance

The *reading distance* is the portion of the travelling distance allotted for the driver to read the message, based upon the time required to read it (reading time). The *Traffic Control Devices Handbook* outlines two methods for calculating the reading time. The first method, used by the Ontario Ministry of Transportation, is described in the following three steps:

1. Allocate 0.5 s per word or number and 1 s per symbol, with a 1-s minimum for the total reading time. This time should only include critical words. Drivers do not need to read every word of each destination listed on a sign to find the one they are looking for. For example, assume they are reading a sign with two destinations: Mercer St. and Union St., each with a direction arrow. Drivers only need to read the word Mercer to realize that is not the street they are looking for and the word Union to know that is their destination. They then only need to look at the arrow for Union St.
2. "If there are more than four words on a sign, a driver must glance at it more than once, and look back to the road and at the sign again. For every additional four words and numbers, or every two symbols, an additional 0.75 s should be added to the reading time." (Ontario Ministry of Transportation Traffic Office, 2001)
3. If the maneuver does not begin before the driver reaches the sign, add 0.5 s to the reading time. This extra time is to account for the extreme viewing angle immediately before the driver passes the sign, which prohibits reading. If the maneuver has already begun, the driver does not need to continue to read the sign, and thus does not need more time.

These three steps are summarized in Table 22-7.

Table 22-7. Three-step method for calculating base reading time.

Step 1	Step 2	Step 3
Base Reading Time (BRT)	**Are there more than 4 words?**	**Does the maneuver initiate before passing the sign?**
BRT (s) = $0.5x + 1y$ where: x = the number of critical words/ numbers in the message y = the number of critical symbols in the message	**Yes**: Add time based on the BRT $2 < \text{BRT} \leq 4$ Add 0.75 s $4 < \text{BRT} \leq 6$ Add 1.50 s $6 < \text{BRT} \leq 8$ Add 2.25 s …etc	**Yes**: Add 0 s
	No: Add 0 s	**No**: Add 0.5 s

Another method for calculating reading time, cited in previous studies, applies to complex signs in high-speed conditions. The formula provided is:

$$\text{Reading Time (s)} = 0.31\ (\text{Number of Familiar Words}) + 1.94$$

After finding the reading time, convert it into a reading distance by multiplying by the travel speed.

Step 2. Calculate the Decision Distance

The *decision distance* is the distance required to make a decision and initiate any maneuver, if one is necessary. After reading the sign, the driver needs this time to decide his/her course of action based upon the sign's message. Decision times range as follows:

- 1 s for simple maneuvers (e.g., stop, reduce speed, choose or reject a single destination from a D1-1 sign)
- 2.5 s or more for complex maneuvers (e.g., two choice points at a complex intersection)

After finding the decision time, convert it into the decision distance by multiplying by the travel speed.

Step 3. Calculate the Maneuver Distance

The *maneuver distance* is the distance required to complete the chosen maneuver. The maneuver distance depends on the course of action decided upon by the driver and the travel speed. The sign placement should consider all of the maneuvers that could be chosen based upon the message.

An example of required maneuver distances is provided in Table 22-8 for lane changes in preparation for a turn. These distances do not apply to situations in which drivers must stop. For high-volume roadways, more time may be needed to find a gap, while for low-volume roadways, some of the deceleration distance may overlap with the lane change distance.

Table 22-8. Maneuver distances required for preparatory lane changes.

Operating Speed (mi/h)	Gap-Search Distance (ft)	Lane Change Distance (ft)	Deceleration Distance (ft)
Non-Freeway Maneuver Distance Requirements			
25	66	139	77
35	92	195	154
45	119	251	257
55	145	306	385
Freeway Maneuver Distance Requirements			
55	218	306	308
65	257	362	462
70	277	390	549

Source: Pline (2001)

Step 4. Calculate the Information Presentation Distance

The *information presentation distance* is the total distance from the choice point (e.g., intersection) at which the driver needs information. This distance is calculated using the following formula:

$$\text{Information Presentation Distance} = \text{Reading Distance} + \text{Decision Distance} + \text{Maneuver Distance}$$

Step 5. Calculate the Legibility Distance

The *legibility distance* is the distance at which the sign must be legible. This distance is based upon the operating speed and the advance placement of the sign from the choice point. The legibility distance is calculated using the formula below:

$$\text{Legibility Distance} = \text{Information Presentation Distance} - \text{Advance Placement}$$

Step 6. Calculate the Minimum Letter Height

The *minimum letter height* is the height required for the letters on the sign based upon the legibility distance calculated above. It is also based upon the legibility index provided in the MUTCD (30 ft/in.).

$$\text{Minimum Letter Height (in.)} = \frac{\text{Legibility Distance (ft)}}{\text{Legibility Index (ft/in.)}}$$

Another consideration is the minimum symbol size. The minimum symbol size is based upon the legibility distance of the specific symbol that is being used. Table 22-9 contains daytime legibility distances for five types of symbols based upon research (Dewar et al., 1994).

From these legibility distances, we can obtain two general trends: (1) legibility distances vary by sign type and (2) legibility distances are greatly reduced for older drivers. Legibility distances for symbols are generally greater than for word messages.

Example Application

As an example, a driver approaches an intersection on a 35-mi/h (51 ft/s) roadway. The driver needs to read a simple designation sign (D1-1) that contains one destination word and

Table 22-9. Daytime legibility distances of five symbol types by age group.

Symbol Type	Number of Signs	Daytime Legibility Distances (ft)			
		Young	Middle-Aged	Old	Mean
Warning	37	736.4	714.7	581.5	677.6
School	2	573.3	634.7	501.2	569.7
Guide	21	472.3	461.5	366.0	433.3
Regulatory	12	464.4	437.9	367.4	423.1
Recreational	13	321.1	292.6	228.9	280.8

one symbolic arrow. The sign is placed 200 ft in advance of the intersection. The legibility index is assumed to be 30 ft/in. (FHWA, 2009). See Figure 22-9.

1. Reading Distance (ft) = [(1 s/word)(1 word) + (0.5 s/symbol)(1 symbol)](51 ft/s) = 77 ft
2. Decision Distance (ft) = (1 s/simple decision)(1 simple decision)(51 ft/s) = 51 ft
3. Maneuver Distance (ft) = Gap Search + Lane Change + Deceleration = 92 ft + 195 ft + 154 ft = 441 ft
4. Information Presentation Distance (ft) = Reading Distance + Decision Distance + Maneuver Distance = 569 ft
5. Legibility Distance = Information Presentation Distance – Advance Placement = 569 ft – 200 ft = 369 ft
6. Letter Height = (369 ft)/(30 ft/in.) = 12 in. (when rounded to the nearest inch)

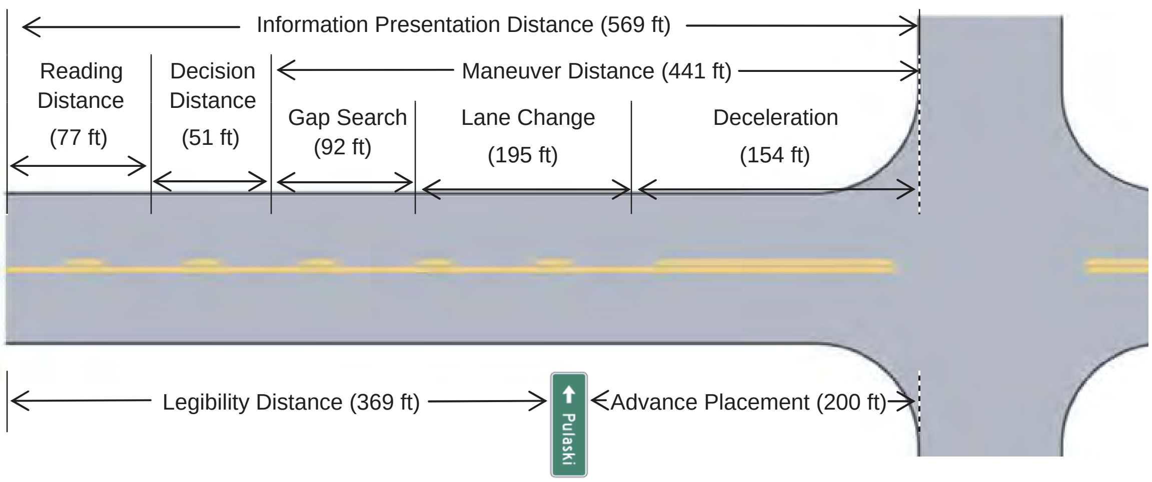

Figure 22-9. Graphic illustrating the example application of a driver approaching an intersection.

Tutorial 6: Calculating Appropriate CMS Message Length under Varying Conditions

The amount of information that can be displayed on a CMS is limited by the amount of time that the driver has to read the message. This amount of time in turn is determined by the legibility distance of the sign and the traveling speed of the passing vehicle. The *legibility distance* is the maximum distance at which a driver can first read a CMS message. According to Dudek (2004), this distance depends upon a number of factors including:

- Lighting conditions
- Sun position
- Vertical curvature of the roadway
- Horizontal curvature of the roadway
- Spot obstructions
- Rain or fog
- Trucks in the traffic stream

These obstructions and visibility limitations reduce the amount of time that the sign is within view or legible, ultimately requiring a reduction in the amount of information that is displayed on the CMS. The information that can be displayed is measured in information units. An information unit is a measure of the amount of information presented in terms of facts used to make a decision. For example, the location of the problem, the audience that is affected by the problem, and the recommended action to take are each 1 information unit. To determine the appropriate number of information units for display on a CMS, the following steps should be considered.

Step 1. Determine the Legibility Distance for the CMS

The maximum legibility distance for a CMS depends on the design characteristics of the sign (Dudek, 2004). These characteristics include the display type, character height, character width, character stroke width, and the font displayed. The base legibility distances found in Table 22-10 are presented in Dudek (2004) and are based on the results of several studies. The distances are based on all uppercase letters, 18 in. character heights, approximately 13 in. character widths, and approximately 2.5 in. stroke widths. Note that all of the information for light-emitting diode signs provided in this tutorial applies only to the newer aluminum indium gallium phosphide (or equivalent) LEDs.

Table 22-10. CMS legibility distances for varying lighting conditions.

Lighting	Legibility Distances (ft)			
	Light-Emitting Diode	Fiberoptic	Incandescent Bulb	Reflective Disk
Mid-Day	800	800	700	600
Washout	800	800	700	400
Backlight	600	500	400	250
Nighttime	600	600	600	250

Source: Dudek (2004)

Step 2. Use the Driver Speed to Find the Base Maximum Number of Information Units Allowed in a Message

The maximum number of information units is derived from the legibility distance of the CMS (which depends on the technology used) and the speed of the passing vehicles. The faster that the passing drivers are going, the less time they have to read the CMS message. Also, because the legibility distance of the sign depends upon the technology used, the number of information units also varies with the technology that is used. Finally, the diverse technologies perform differently under changing conditions. Table 22-11 presents the base maximum number of information units that can be presented for assorted CMS technologies, under several ambient lighting conditions.

Step 3. Adjust for Adverse Roadway and Environmental Conditions

There are many roadway and environmental conditions that reduce the visibility of CMSs and thus require a reduction in information units. Dudek (2004) provides further guidance on the exact number of information units that should be used under different conditions. The following sections describe how various conditions and factors lead to trade-offs in the number of information units that may be displayed.

Vertical Curves

The reduction in information units required for vertical curves depends on the design speed of the curve as well as the CMS offset from the road and mounting height. The following general relationships apply to CMSs on vertical curves:

- As the design speed of the curve decreases, the number of information units that may be used decreases.
- As the horizontal offset from the road increases, the number of information units that may be used decreases.
- As the mounting height of the CMS decreases, the number of information units that may be used decreases.

Table 22-11. Maximum number of information units per message for various technologies at different speeds.

Lighting	Maximum Information Units per Message											
	Light-Emitting Diode			Fiberoptic			Incandescent Bulb			Reflective Disk		
	0-35 mi/h	36-55 mi/h	56-70 mi/h	0-35 mi/h	36-55 mi/h	56-70 mi/h	0-35 mi/h	36-55 mi/h	56-70 mi/h	0-35 mi/h	36-55 mi/h	56-70 mi/h
Mid-Day	5	4	4	5	4	4	5	4	3	5	4	3
Washout	5	4	4	5	4	4	5	4	3	4	3	2
Backlight	4	4	3	4	3	2	4	3	2	2	1	1
Nighttime	4	4	3	4	4	3	4	3	3	3	2	1

Source: Dudek (2004)

In general, permanent CMSs that are mounted over the roadway are not affected by crest vertical curves (Dudek, 2004).

Horizontal Curves

The main concern with CMSs located on horizontal curves is the obstruction of the sign by roadside objects. Permanent CMSs that are mounted above or adjacent to the travel lanes will likely be high enough to be seen over any roadside obstructions. However, portable CMSs are usually closer to the ground and more likely to be obscured by obstructions. In general, the number of information units that may be used decreases when:

- The obstruction gets closer to the roadway
- The curve radius decreases (i.e., for tighter curves)

Rain

Rain does not generally affect CMSs (Dudek, 2004). However, when the intensity of the rainfall increases to 2 in./h or more, the visibility of the sign can be impacted. When the operating speed of the roadway is over 55 mi/h, Dudek (2004) recommends that the number of information units displayed on portable LED CMSs should be reduced by 1 information unit. Portable LED CMSs often use fewer pixels per character, and thus have lower luminance levels per character than permanent CMSs, which are relatively unaffected even in heavy rainfall. Therefore, signs utilizing other technologies should use fewer information units in heavy rainfall.

Fog

Fog can affect visibility even more than heavy rain. Generally, Dudek (2004) does not recommend a reduction in information units for permanent LED CMSs because of fog. A reduction is not necessary because of the high character luminance and contrast of permanent LED CMSs. However, portable LED CMSs require a reduction. The number of information units that may be used decreases when:

- The visibility range decreases
- The offset from the road increases

Trucks on the Roadway

Large trucks pose sight obstructions for other vehicles on the roadway. When a driver's view of a CMS is obscured by a truck, the driver has the option to change his/her traveling speed or position to see around the truck. However, as the number of trucks on the roadway increases, the amount of space that is available for drivers to do this repositioning decreases. Thus, the more trucks that are on the roadway, the more likely they are to impair the view of a CMS for other drivers.

Step 4. Adjust for Blanking Time

Greenhouse (2007) found that inserting a 300-ms blank screen between phase 1 and phase 2 of a portable message sign improves comprehension. The study is further discussed in the guideline for *Displaying Messages with Dynamic Characteristics.* Although the blanking time was only tested between phases 1 and 2 (not between 2 and 1), it is reasonably conceivable that drivers who see a blank between phases 1 and 2, but not between phases 2 and 1, would reverse the order of the phases and possibly have trouble understanding the message. Dudek (1992) recommends that blank time and/or asterisks should be displayed between cycles of a message that contains three or more phases (on one-word or one-line signs). Because one-word and one-line signs are more limited in the amount of information that they can display at one time, the phases may not make sense independently and drivers who read later phases before phase 1 may not understand the message. Thus, giving an indication of where the message is in the cycle gives drivers an idea of their location in the cycle.

Overall, drivers may use the blanking time to determine where they are in the message cycle, even before the message is legible to them. There are additional benefits in terms of message comprehension as shown by Greenhouse (2007). However, the insertion of blanking time reduces the total available time for the driver to read the message, potentially requiring a reduction in information units. Thus, there is a trade-off between the benefits of providing blanking time and the number of information units that may be contained in the message.

Step 5. Display the Resulting Number of Information Units

After the calculations and adjustments from Steps 1 through 4 are performed, the result will be the number of information units that may be displayed in the message. If there are still more information units in the message than should be displayed, they should be reduced using the following steps, until the appropriate number of information units is reached (steps and examples adapted from Dudek (2004)).

Step 5A: Omit and Combine Information Units

First, attempt to reduce the number of information units without losing content by following the steps below.

- Omit unimportant words and phrases

  Example:

Original Message:	Shortened Message:
ROAD CLOSED AHEAD	ROAD CLOSED
DUE TO CONSTRUCTION	1 MILE
FOLLOW DETOUR ROUTE	FOLLOW DETOUR

  The word “Ahead” is unnecessary as drivers will assume the closure is ahead. The reason is less important than the location of the closure.

- Omit redundant information

Example:

Original Message:	Shortened Message:
MAJOR ACCIDENT ON I-276 NORTH PAST I-80 2 LEFT LANES CLOSED KEEP RIGHT	MAJOR ACCIDENT PAST I-80 2 LEFT LANES CLOSED

If the CMS is on I-276, the same freeway as the accident, the information is evident to the drivers and may be omitted. The information units "2 Left Lanes Closed" and "Keep Right" are redundant because drivers can assume that if the two left lanes are closed, they will need to move to the right.

- Combine base CMS elements

Example:

Original Message:	Shortened Message:
TRUCK ACCIDENT PAST I-80 ALL LANES CLOSED AT I-80 I-287 NORTH TRAFFIC EXIT AT I-80 FOLLOW DETOUR	FREEWAY CLOSED EXIT AT I-80 FOLLOW DETOUR

In the example above, the incident descriptor, incident location, and lanes closed message elements are combined into the information unit "Freeway Closed". The location of the closure can be eliminated because the action element "Exit at I-80" describes the location.

Step 5B. Reduce the Number of Audiences in the Message

Example:

Original Message:	Shortened Message:
I-76 CLOSED BEST ROUTE TO PHILADELPHIA/I-95 USE RTE-73 NORTH	I-76 CLOSED BEST ROUTE TO PHILADELPHIA USE RTE-73 NORTH

When using this reduction technique, message designers must use their judgment to decide which audience is more important to address in the message. In the previous example, the audience "Philadelphia/I-95" was reduced from 2 information units to 1 information unit, "Philadelphia".

Step 5C. Use Priority Reduction Principles

If the message still contains more information units than should be displayed, the information units should be reduced in order of priority. The priority order is derived from the information drivers need the most in order to make driving decisions. In Table 22-12, the information units are listed in priority order, with number 1 being the highest priority information.

If the closure is due to roadwork, the effect on travel and good reason for following the action should be eliminated. Even though the incident/roadwork descriptor is useful to drivers, it may be replaced with the lanes closed element if necessary. When choosing information units to eliminate, the designer should start deleting units from the bottom of these priority lists first (i.e., element numbers 8 or 6). More examples of the application of these steps can be found in Dudek (2004).

Table 22-12. Order of priority for information units.

Lane Closures	Freeway/Expressway Closures
1. Incident Descriptor	1. Closure Descriptor
2. Incident Location	2. Location of Closure
3. Lanes Closed	3. Speed Reduction Action (if needed)
4. Speed Reduction Action (if needed)	4. Diversion Action
5. Diversion Action (if needed)	5. Audience for Action (if needed)
6. Audience for Action (if needed)	6. Effect on Travel (if needed)
7. Effect on Travel (if needed)	
8. Good Reason for Following Action (if needed)	

CHAPTER 23

References*

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CHAPTER 24

Glossary

Acceptable Gap Distance—The size of the gaps in major-road traffic typically accepted by drivers turning from a minor road to provide sufficient time for the minor-road vehicle to accelerate from a stop and complete a turn without unduly interfering with major-road traffic operations.

Accessible Pedestrian Signals (APS)—Equipment for use at signalized intersections that communicates pedestrian signal timing information in non-visual formats. Features include pushbutton locator tone, tactile arrow, pushbutton information message, automatic volume adjustment, alert tone, actuation indicator, tactile map, Braille and raised print information, extended button press, passive pedestrian detection, and clearance interval tones.

AMBER Alert—An urgent broadcast regarding child abductions.

Apparent Radius—The curve radius as seen from the driver's perspective, which, in some cases, can make the curve appear distorted—either flatter or sharper—depending on topography and other road elements.

Appropriate Message Length—Sign message lengths that drivers have time to read and comprehend as they pass the sign.

Arcminute—One-sixtieth (1/60) of one degree (1°).

Arrow Panel Visibility—A roadway sign condition dependent on a number of factors, including the capability of the lamps in the panel, the type of roadway, the physical location of the panel, and the panel's relation to horizontal and vertical curves, ambient light, and weather.

Arrow-per-lane (APL) Signs—Large or grouped signs providing every individual lane with its own arrow to improve driver navigation.

Behavioral Framework for Speeding—Conceptual overview of the key factors relevant to speed selection, as well as their relationship to potential speeding countermeasures.

Bilingual Information—Information that is presented in more than one language on changeable message signs (CMSs).

Blank-out/Blanking—The period of time, or scheduled phase, when sign readouts are not being used.

Bollard—A thick vertical post sometimes used to control pedestrian and vehicular traffic. Bollard-mounted lighting can be used to provide vertical illuminance on pedestrians at crosswalks for improved visibility.

Broad Spectrum—Light that contains a wide range of wavelengths (colors) across the visible spectrum. A broad-spectrum luminaire contains sufficient color content that humans can readily discriminate the colors of objects illuminated by it.

Bulbout—A curb extension going past the sidewalk or curb line into the street. Bulbouts reduce the street pavement width in order to improve pedestrian crossings by shortening crossing distances, reducing the time pedestrians are exposed to traffic, improving pedestrian and motorist visibility, and reducing traffic speeds.

Candela—The International System of Units (SI) base unit of luminous intensity.

Caution Mode Configuration—Arrow panel mode C, which provides flashing non-directional information to increase safety near highway work zones by providing early warning information to drivers indicating that caution is required while approaching and traveling through the work zone.

Changeable Message Sign (CMS)—CMSs are electronic, reconfigurable signs placed above or near the roadway and are used to inform motorists of specific conditions or situations. Also referred to as variable message signs (VMSs) or dynamic message signs (DMSs).

Clear Zone—The roadside border area that is available for drivers to safely stop or gain control of an errant vehicle. This area may include a shoulder, recoverable or non-recoverable slopes, and run-out areas that are smooth and clear of obstructions. See FHWA (2011).

Clearance Interval—The period of time necessary for safe transitions in right-of-way (ROW) assignment between crossing or conflicting flows of traffic, including pedestrian activity; a combination of the yellow clearance interval plus the red clearance interval or an all-red interval.

Clearing Distance—The distance a vehicle travels beginning at the time the signal changes to yellow and ending at the time the signal changes to red.

Closed-Loop Compensatory Component—Part of the steering control process in which drivers continually monitor and adjust for deviations in position on the road based on feedback from near-field visual cues.

Cognitive Preparation—The various active mental activities that can influence response times and decisions of drivers and includes such things as driver expectancies, situational awareness, a general sense of caution, and where attention is being directed by the driver.

Color Spectrum—See Spectrum.

Complexity—A function or level describing how much information is being provided and how difficult it is to process.

Complexity of Sign Information—The number of information units being presented as part of roadway sign messages.

Comprehension—The combination of completing a task at hand, e.g., reading a sign, plus the process of making the resultant decision, e.g., right or left turn in response to the sign's information.

Cone—The portion of the roadway scene on the right-hand side of the roadway where a driver would typically look for road signs.

Conspicuity—The ease in seeing and locating a visual target, including signage, vehicles, bicycles, or pedestrians. In the context of road signs, it represents how easy it is to distinguish a sign from the surrounding visual environment.

Continuation Distance—The distance that a vehicle travels prior to the descent of the entry gates at a railroad crossing.

Counterbeam Lighting—A lighting technique whereby the light falls on objects from a direction opposite to the traffic. Counterbeam lighting is characterized by a luminous intensity distribution that is asymmetrical and has the maximum luminous intensity aimed against the direction of normal traffic flow.

Crest Horizontal Curve—A horizontal curve that also contains a vertical, concave down, component of curvature.

Critical Gap—For design purposes, the critical gap represents the gap between successive oncoming vehicles that average drivers will accept 50% of the time (and reject 50% of the time).

Cross Section—The width of the lane.

Cross Slope—The transversal slope of the roadway (described as a percentage) with respect to the horizon.

Crossbuck—A railroad warning sign with two slats of wood or metal fastened together on a pole in a letter X formation with the word "Railroad" on one slat and "Crossing" on the other, black letters on a white background. Crossbucks are sometimes supplemented by other warning devices such as flashing lights, a bell, a “Yield” sign, a “Stop” sign, and/or a descending gate to prevent traffic from crossing the tracks.

Decibel (dB) Level—A measurement that expresses the power or intensity magnitude of sound relative to a specified or implied *reference level.* A decibel is one-tenth of a bel, a seldom-used unit.

Decision Sight Distance (DSD)—DSD represents a longer sight distance than is usually necessary and is used for situations in which (1) drivers must make complex or instantaneous decisions, (2) information is difficult to perceive, or (3) unexpected or unusual maneuvers are required.

Design Consistency—Conformance of a highway’s geometric and operational features with driver expectancy.

Dilemma Zone—The portion of the roadway formed between (1) the clearing distance to the intersection (the distance the vehicle travels between the time the signal changes to yellow to the time the signal changes to red) and (2) the stopping distance (the distance traveled by the vehicle between the times the signal changes to yellow to the time when the vehicle actually stops) when the stopping distance is greater than the clearing distance. The size of the dilemma zone is relative to the situation; it is not a fixed area.

Driver Expectations—The driver’s readiness to respond to situations, events, and information in predictable and successful ways.

Driver Fatigue—A general psycho-physiological state that diminishes an individual’s ability to perform the driving task by reducing alertness and vigilance.

Drop-off—Deterioration of roadways caused when the edges of the pavement become destabilized and eroded, resulting in a difference in height between the pavement surface and the roadside surface.

Dynamic Characteristics—Message properties that specify character movement such as time to display each message phase, to display blanking between phases of a multiphase message, and to flash one or more lines of a message.

Dynamic Dilemma Zone—A road segment on approach to an intersection which varies in length based on fluctuations in vehicle speeds and number.

Dynamic Late Merge Systems—These systems, developed for use in work zone lane closure situations, utilize a series of changeable message signs and static work zone signs to provide merge information to the driver. The information is based upon the current traffic volume through the work zone and supports early merging when the traffic flow is light and late merging (closer to the gore point) when the traffic volume is heavier.

Dynamic Message Sign (DMS)—DMSs are electronic, reconfigurable signs placed above or near the roadway and are used to inform motorists of specific conditions or situations. Also referred to as changeable message signs (CMSs) or variable message signs (VMSs).

Effective Length of the Passing Lane—The physical length of the passing lane plus the distance downstream to the point where traffic conditions return to a level similar to that immediately upstream of the passing lane.

Effects of Roadway Factors on Speed—The impact of geometric, environmental, and traffic factors on driving speed under free-flow conditions in tangent roadway sections.

Empirical Bayes—A method in which empirical data are used to estimate conditional probability distributions.

Exit Gate Clearance Time—The amount of time provided to delay the descent of the exit gate arm(s) after entrance gate arm(s) begin to descend at a railroad crossing.

Factors Affecting Acceptable Gap—These factors are the driver, environment, and other situational factors—such as traffic volume, wait times, familiarity with the roadway or oncoming vehicle size—that cause most drivers or specific groups of drivers (e.g., older drivers) to accept smaller or larger gaps than they would otherwise accept under normal conditions.

Fatal Accident Reporting System (FARS)—National Center for Statistics and Analysis (NCSA) data system.

Four-Quadrant Gate—A set of four descending gates to stop traffic at railroad crossings which consists of one gate before and one gate after the railroad tracks for each of the two lanes of traffic.

Foveal Vision—Central vision of the eye. The fovea, located in the pit of the retina, is the source of the eye's high visual acuity capability.

Free-Flow Speed—Free-flow speed is defined as conditions in which a driver has the ability to choose a speed of travel without undue influence from other traffic, conspicuous police presence, or environmental factors.

Fundus—The interior surface of the eye, opposite the lens, and includes the retina, optic disc, macula and fovea, and posterior pole.

Gap—The time interval between two successive vehicles, measured from the rear of a lead vehicle to the front of the following vehicle, adapted from *Traffic Engineering Handbook* (Pline, 1999).

Gate Delay—The length of time between the start of the flashing lights and the initiation of the descent of the entry gate arm at railroad crossings.

Gate Interval Time—The length of time between the initiation of the descent of the entry gate and the initiation of the descent of the exit gate at a crossing with a four-quadrant gate device.

Gate-rushing—Gate-rushing is when drivers do not stop at railroad crossings and drive under the gate arms as they are descending or drive around gate arms that are already in the lowered position.

Glare—A visual phenomena which occurs when the intensity of a light source within the visual field is substantially greater than the visual adaptation level, causing physical discomfort or pain (discomfort glare) and/or reduced visibility (disability glare).

Glare Screens—Visual barriers designed to shield drivers from glaring light from oncoming headlamps. Glare screens are often mounted on median barrier walls and come in a variety of forms, including vertical paddles, concrete barriers, wire or plastic mesh screens, etc. Shrubbery and other landscaping elements can also be used as glare screens.

Grade Severity Rating System—A simulation model that establishes a safe descent speed for the grade based upon a predetermined brake temperature limit.

HAWK Signal—A new type of overhead beacon signal to assist pedestrians at unsignalized crosswalks on high-volume traffic streets.

High Pressure Sodium (HPS) Lamp—A type of lamp for street lighting that operates using an electric arc through sodium vapor under high pressure. HPS lamps glow with a characteristically yellow light.

Highway Systems—The combination of three major components—the road (local roads, collectors, arterials and freeways), traffic control, and users with or without a vehicle.

Horizontal Curves with Vertical Sag—A horizontal curve that also contains a vertical, concave up, component.

Human Factors—A scientific discipline that tries to enhance the relationship between devices and systems and the people who are meant to use them through the application of extensive, well-documented, and fully appropriate behavioral data that describe and analyze the capabilities and limitations of human beings.

Independent Alignments—Roadway design such that opposing lanes are developed independently of each other. The opposing alignments may or may not run parallel to each other. Also, they may be separated horizontally by geographic, landscaping, or other features. Similarly, they may be separated vertically on hillsides or other steep grades.

Induction Lamp—A type of lamp for street lighting that uses electromagnetic fields rather than electrodes to wirelessly transfer power to the interior of the lamp. Radio waves are typically used to energize either a bulb filled with sulfur or metal halides or a tube based on conventional fluorescent lamp phosphors.

Information Units—A measure of the amount of information presented in terms of facts used to make a decision.

Intersection Sight Distance (ISD)—The stopping sight distance required at intersections. Actual ISDs will differ, depending on the type of intersection and maneuver involved.

Lag—The time interval from the point of the observer to the arrival of the front of the next approaching vehicle (Lerner et al., 1995, pp. 58–59).

Lane Drop Markings—Pavement markings that consist of short wide lines with short gaps used to delineate a lane that becomes a mandatory turn or exit lane.

Legibility Distance—The minimum distance at which a sign must become legible to a typical driver. It is calculated as a function of the time it takes a driver to read the sign, interpret the sign, and execute maneuvers that comply with the sign's message.

Legibility Index—The distance at which a given unit of letter height is readable.

Long-Range Guidance—Driving preview time for drivers of at least 5 s.

Looming—One of several dynamic characteristics of message signs, this term refers to increasing the size of text or symbols over time in a message display.

Low Pressure Sodium (LPS) Lamp—A type of lamp for street lighting that operates using an electric arc through sodium vapor. LPS lamps operate at lower pressure than HPS lamps, and they are nearly monochromatic yellow in color.

Luminaire—A lighting fixture that consists of one or more electric lamps, lamp housings, reflectors, mast, wiring, and other necessary parts.

Luminaire Cutoff Pattern—The distribution of intensities from a luminaire around the point at which the luminaire emits no light. A luminaire with full cutoff projects less than 10% of rated lumens beyond 80 degrees from nadir and no light at or above 90 degrees from nadir. The nadir is defined as the angle that points directly downward (0 degrees) from the luminaire.

Luminance—Luminance is the luminous intensity per unit area of light measured as candela per square meter (cd/m^2).

Luminous Intensity—A measure of the perceived power emitted by a light source in a particular direction per unit solid angle.

Lux—The International System of Units (SI) unit of illuminance and luminous emittance.

Maneuver Time (MT)—The amount of time required to safely complete a maneuver. MT is primarily affected by the physics of the situation, including vehicle performance capabilities, tire-pavement friction, road-surface conditions (e.g., ice), and downgrades, and to a lesser extent by driver-related factors (e.g., deceleration profile), although these factors are highly situation specific because the maneuvers encompass a broad range of actions (e.g., emergency stop, passing, left turn through traffic).

Mental Models—The system user's internal understanding and representation of an external reality.

Mesopic Lighting—Light conditions under which visual sensitivity is shifted toward the blue/green portion of the visible spectrum compared to vision under photopic (daytime) lighting, thus making objects and clothing in this part of the spectrum more visible under these conditions. See photopic lighting.

Metal Halide Lamp—A type of lamp for street lighting that operates using an electric arc through mercury vapor under high pressure. Metal halide salts added to the mercury glow at different wavelengths yielding a relatively white light.

Most Meaningful Information (MMI)—Information sought by drivers for particular road location and point in time through scanning the road environment in front of, behind, and to the sides of the vehicle they are driving.

Nighttime Driving—The situation in which motorists' visibility while driving in darkness on rural roads is limited; roadway features, objects in the roadway, or pedestrians ahead are less visible depending upon headlamp intensity, ambient lighting, and presence or absence of oncoming headlamp glare.

Open-Loop Anticipatory Control Process—Part of the steering control process in which drivers predict road curvature and required steering angle based on far-field visual cues.

Optic Flow—The visual pattern caused by moving forward, in which points close to the point of expansion move outward slower than points more peripheral to it. This information is directly used by the driver's visual system to perceive motion.

Passing Lane—A lane added in one or both directions of travel on a two-lane, two-way highway to improve passing opportunities.

Passing Sight Distance (PSD)—The amount of distance ahead a driver must be able to see in order to complete a passing maneuver without cutting off the passed vehicle before meeting an opposing vehicle that appears during the maneuver.

Pavement Classifications—The type and texture of paving material affects how light reflects from the road surface. The International Commission on Illumination (Commission Internationale de l'Eclairage or CIE) has developed four road surface classifications. Class R1 surfaces have primarily diffuse reflectances, Class R2 surfaces have mixed diffuse and specular reflectances, Class R3 surfaces have slightly specular reflectances, and Class R4 surfaces have mostly specular reflectances (see IESNA 2000).

Pavement Drop-off—Drop-offs are caused when the edges of pavement are destabilized and eroded, resulting in a difference in height between the pavement surface and the roadside surface.

Perception-Identification-Emotion-Volition (PIEV) Time—The total time from perception to completing a reaction.

Perception-Reaction Time (PRT)—The time a driver takes to process information, typically defined as the period from the time the object or condition requiring a response becomes visible in the driver's field of view to the moment of initiation of the vehicle maneuver. Per AASHTO (2004), bits of information on a scale from 0 to 6 bits is processed by the average driver at about 1 and 1.5 bits of information per second for unexpected and expected situations, respectively.

Perceptual Requirements—The visual information about the roadway and surrounding environment that drivers need to judge road curvature, determine lane position and heading, etc.

Phase (for message signs)—The text that is displayed at a single point in time on a message sign.

Photopic Lighting—Light conditions under which visual appearance is stronger at the yellow portion of the visible spectrum compared to vision under mesopic (nighttime) lighting when visual sensitivity is shifted toward the blue/green part of the spectrum. See mesopic lighting.

Point of Expansion—During forward motion, the point in the forward field that appears stationary relative to the observer (the observers' actual destination), and from which all other points are seen as moving away.

Post-Mounted Delineators (PMDs)—A type of marking device used to guide traffic; a series of retroreflective devices mounted above the roadway surface and along the side of the roadway to indicate the alignment of the roadway.

Preview Sight Distance (PVSD)—PVSD is a measure of driver sight distance based on the assumption that "the driver views or previews the roadway surface and other cues that lie ahead to obtain the information needed for vehicular control and guidance" (Gattis and Duncan, 1995).

Psychomotor Requirements—The control actions (e.g., steering-wheel movements; foot movements to press brake, etc.) that drivers must make to maintain vehicle control or to facilitate other information acquisition activities.

Raised Pavement Markers (RPM)—A variety of three-dimensional devices used in conjunction with pavement markings to mark lane boundaries. They often have a reflective surface to increase visibility and produce a noticeable vibration or physical sensation when in contact with vehicle tires.

Red Light Running—Situations when drivers enter a signalized intersection when a red light is being presented.

Retroreflective Raised Pavement Markers (RRPM)—Raised pavement markers affixed to the road surface that are designed to reflect light directly back to the light source.

Retroreflectivity—The property allowing a surface to reflect a large portion of its light directly back to or near its source.

Roadway Shoulder—See Shoulder.

Roundabout Intersection—As defined by the MUTCD, roundabouts are circular intersections with yield control at entry, permitting a vehicle on the circulatory roadway to proceed, and deflecting the approaching vehicle counter-clockwise around a central island (FHWA, 2009).

Roving Eye Treatments—Pedestrian or driver signals which include a pair of animated eyes as part of the lighted display, intended as a reminder to watch for vehicle movement (for pedestrians) or to watch for pedestrian movements (for drivers).

Safety Edge—A wedge-shaped asphalt material placed between the roadway and the shoulder, which can be used as a drop-off countermeasure.

Serial Processing—A chain of events in which one step does not begin until the previous step is complete that is used to model some driver behavior.

Shared-Use Lanes—Roadways or lanes used concurrently by vehicles, bicyclists, or pedestrians in either rural or urban areas.

Sharrows—Shared-lane markings.

Short-Range Guidance—Preview time for drivers of up to 3 s.

Shoulder or Roadway Shoulder—A portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles; for emergency use; and for lateral support of the subbase, base, and surface courses. Also may be used by non-motorized traffic.

Shoulder Drop-off—A difference in height between the pavement surface and the roadside surface caused when the edges of pavement become destabilized and eroded.

Shoulder Rumble Strips (SRSs)—A raised or grooved pattern on the shoulder of a travel lane to provide a tactile or audio alert to the driver.

Sight Distance (SD)—The distance that a vehicle travels before completing a maneuver in response to some roadway element, hazard, or condition that necessitates a change of speed and/or path. SD is based on (1) a perception-reaction time (PRT) required to initiate a maneuver (pre-maneuver phase) and (2) the time required to safely complete a maneuver (MT).

Sight Distance at Left-Skewed Intersections—The available sight distance to the driver's right side for a vehicle crossing a major road from a left-skewed minor road (where the acute angle is to the right of the vehicle).

Sight Distance at Right-Skewed Intersections —The available sight distance to the driver's left side for a vehicle crossing a major road from a right-skewed minor road (where the acute angle is to the left of the vehicle).

Sign Comprehension—The driver's or road user's ability to interpret the meaning of a sign. The ability to comprehend and use signs is associated with three stages: legibility, recognition, and interpretation. Sign comprehension can also consist of the sign reading task plus the process of making the resultant decision, e.g., right or left turn in response to the sign's information.

Sign Design—Design parameters of signs that impact the legibility of text placed on the sign, including retroreflectivity, legend color, font size, and font style.

Sign Legend—The text and/or symbols composing the message of a sign.

Sign Legibility—Specific design characteristics of signs that contribute to the drivers' ability to perceive and understand the sign's message.

Sign Legibility Index—An index created by the USSC to calculate sign letter height. To determine letter height divide the viewer reaction distance by the appropriate legibility index value (which varies depending on illumination, font style and case, as well as font color contrast to background).

Sign Recognition—The ability of the driver to readily distinguish the sign, especially in the context of other signs and stimuli.

Small Target Visibility Method—One method used to calculate or measure road lighting levels based on visibility of a small target. Visibility is calculated using target size and reflectivity, road reflectivity, veiling luminance, and other factors.

Spectral Power Distribution (SPD)—The distribution of the power of each wavelength in the visual spectrum produced by a light source. The spectral power distribution of a luminaire affects the perceived color of objects illuminated by it and may affect the ability to detect, identify, or discriminate objects under mesopic lighting conditions.

Spectrum—The full range of wavelengths (colors) of light produced by a light source. For example, a low pressure sodium luminaire contains nearly monochromatic yellow light, while an LED light source contains a variety of wavelengths with an abundance of blue relative to the other wavelengths in the spectrum.

Speed Perception—A driver's judgment of how fast he or she is traveling.

Stopping Distance—The distance traveled by a vehicle beginning from the time a traffic signal changes to yellow and ending at the time when the vehicle actually stops.

Stopping Sight Distance (SSD)—The distance from a stopping requirement (such as a hazard) that is required for a vehicle traveling at or near design speed to be able to stop before reaching that stopping requirement. SSD depends on (1) how long it takes for a driver to perceive and respond to the stopping requirement (PRT) and (2) how aggressively the driver decelerates (MT). This distance can be calculated as the sum of driver perception-reaction time + vehicle deceleration, under a range of visibility/traction conditions.

Task Analysis—Identification of basic activities performed by drivers as they navigate different driving scenarios by successively decomposing driving segments into tasks and subtasks/information processing elements.

Title II of the Americans with Disabilities Act (ADA) of 1990—Title II of the ADA is implemented in 28 CFR Part 35, which prohibits discrimination on the basis of disability by public entities. *28 CFR 35.151 New construction and alterations* is available at http://www.ed.gov/policy/rights/reg/ocr/edlite-28cfr35.html#S151.

Train Delay—The amount of time between the gate descent and the train arrival at railroad crossings.

Traffic Engineering—The definition from ITE's *Traffic Engineering Handbook* is "that branch of engineering which applies technology, science, and human factors to the planning, design, operations and management of roads, streets, bikeways, highways, their networks, terminals, and abutting lands" (Pline, 1999).

Truck Escape Ramp—A facility designed and constructed to provide a location for out-of-control trucks to decelerate to a stop, which is also available for use by other vehicles.

Turnout—A widened, unobstructed shoulder area or lane that provides opportunities for slow-moving vehicles to pull out of the through lane and passing opportunities to following vehicles.

Two-Quadrant Gate—A set of two descending gates to stop traffic at railroad crossings which consists of one gate before the railroad tracks for each of the two lanes of traffic.

Veiling Luminance—Uniform luminance that washes over the retina causing a reduction of contrast. Veiling luminance is caused when the eye is exposed to a light source that is substantially more intense than the adaptation level.

Viewer Reaction Distance—The distance a viewer will cover at a given rate of speed and reaction time, which can be calculated by speed of travel (ft/s) times perception-reaction time (s).

Visual Conspicuity—Characteristics of a sign that enable a driver to differentiate the sign from its surrounding environment.

Variable Message Sign (VMS)—VMSs are electronic, reconfigurable signs placed above or near the roadway and used to inform motorists of specific conditions or situations. Also referred to as changeable message signs (CMSs) or dynamic message signs (DMSs).

Warning Time—At railroad crossings, the time between the initiation of the flashing light traffic control devices and the arrival of the train.

Warrant Criteria—Criteria used to determine whether street lighting is warranted at an intersection or other location. Various jurisdictions use nighttime/daytime crash ratios, average daily traffic, and other criteria to determine whether street lighting is likely to provide sufficient safety improvements to justify the expense of installing and operating lighting at the location.

Wayside Horn—An audible warning horn mounted at rail-highway crossings to alert drivers when a train is approaching.

Work Zone Speed Limits—Reduced speed limits used in work zones to maintain safe traffic flow.

Yellow Timing Interval—Duration of the yellow signal indication (also referred to as the "yellow change interval" or "yellow clearance interval").

Zip Merging—Vehicles merging one by one in an alternating pattern.

CHAPTER 25

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CHAPTER 26

Abbreviations*

Δt	Sampling Interval
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ABS	Anti-Lock Braking System
ADA	Americans with Disabilities Act
ADT	Average Daily Traffic
APL	Arrow-per-Lane (Sign)
APS	Accessible Pedestrian Signals
ATIS	Advanced Traveler Information Systems
ASD	Available Sight Distance
BRT	Base Reading Time
CALTRANS	California Department of Transportation
cd	Candela
CIE	Commission Internationale de l'Eclairage
cm	Centimeter(s)
CMS	Changeable Message Signs
CVO	Commercial Vehicle Operations
dBA	Sound intensity measured in decibels (relative to sound pressure level of 20 micropascals). The frequency spectrum is weighted to approximate human hearing.
DMS	Dynamic Message Sign
DSD	Decision Sight Distance
DVRE	Driver, Vehicle, Roadway, and Environment
EL	Edge Line
FARS	Fatal Accident Reporting System
FHWA	Federal Highway Administration
ft	Foot/Feet
g	Acceleration/deceleration equivalent to the rate of acceleration due to gravity. One g equals approximately 9.8 m/s^2.
HAR	Highway Advisory Radio
HAWK	High-Intensity Activated Cross-Walk
HCM	*Highway Capacity Manual*
HFG	*Human Factors Guidelines for Road Systems*
HPS	High Pressure Sodium (Lamp)
HSM	*Highway Safety Manual*
IA	Intersection Angle

*Covers all chapters.

IHSDM	Interactive Highway Safety Design Model
ISD	Intersection Sight Distance
ITE	Institute of Transportation Engineers
km/h	Kilometers per Hour
LC	Lane Change
LD	Legibility Distance
LED	Light-Emitting Diode
LPS	Low Pressure Sodium (Lamp)
m	Meter
mcd	Millicandela
MH	Metal Halide
mi	Mile
mi/h	Miles per Hour
mm	Millimeter
MMI	Most Meaningful Information
MT	Maneuver Time
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
N•m	Newton Meter
NMSL	National Maximum Speed Limit
NTOR	No Turn on Red
PCC	Portland Cement Concrete
PIEV	Perception-Identification-Emotion-Volition
PMD	Post-Mounted Delineator
POV	Principal Other Vehicle
PRT	Perception-Reaction Time
PSD	Passing Sight Distance
PVSD	Preview Sight Distance
R value	Correlation-coefficient
ROW	Right-of-Way
RRPM	Raised Reflective Pavement Marker
RT	Reaction Time
RTOR	Right Turn on Red
s or sec	Second(s)
SAE	Society of Automotive Engineers
SCL	Speed-Change Lane
SD	Sight Distance
SF	Safety Factor
SI	International System of Units
SLIDE	Simplified Location of Information Deficiencies
SPD	Spectral Power Distribution
SR	Sampling Rate
SRS	Shoulder Rumble Strip
SSD	Stopping Sight Distance
SV	Subject Vehicle
SVROR	Single Vehicle Run off Road
TCD	Traffic Control Device
TER	Truck Escape Ramp
USSC	United States Sign Council
UVC	Uniform Vehicle Code

v/c Ratio	Volume-to-Capacity Ratio
VMS	Variable Message Sign
VPD	Vehicles per Day
vph	Vehicles per Hour
VSL	Variable Speed Limit
VTTI	Virginia Tech Transportation Institute
WSS	Weight-Specific-Speed

CHAPTER 27

Equations

Road User Sampling Rate

$$\text{Sampling rate} = f(\text{user, operations, highway, environment}) \qquad 4\text{-}2$$

Road User Information Database for Making Decisions

$$\text{Information(t)} = \text{Information(t-1)} + \text{changes during } \Delta t \qquad 4\text{-}3$$

Where:

t = time
Δt = sampling interval

Sight Distance

Sight Distance = Distance traveled while driver perceives, makes decisions about, and initiates action in response to roadway element (PRT) + Distance traveled while the driver completes an appropriate maneuver (MT) 5-2

Stopping Sight Distance (SSD) Design Values

Metric: $$SSD = 0.278Vt_{RT} + 0.039\frac{V^2}{a} \qquad 5\text{-}4$$

Where:

t_{RT} = perception-reaction time
V = design speed, km/h
a = deceleration level, m/s^2

US Customary: $$SSD = 1.47Vt_{RT} + 1.075\frac{V^2}{a}$$

Where:

t_{RT} = perception-reaction time
V = design speed, mi/h
a = deceleration level, ft/s^2

Decision Time

A	$t = 3.0$ s	Metric:	Where:	5-8
		$d = 0.278Vt + 0.039\frac{V^{t}}{a}$	V = design speed (km/h) a = driver decel. (m/s^2)	
B	$t = 9.1$ s	US Customary:	Where:	
		$d = 1.47Vt + 1.075\frac{V^{t}}{a}$	V = design speed (mi/h) a = driver decel. (ft/s^2)	
		Metric:	Where:	
C	$t = 10.2 - 11.2$ s			
		$d = 0.278Vt$	$d = 0.278Vt$	
D	$t = 12.1 - 12.9$ s			
		US Customary:	Where:	
E	$t = 14.0 - 14.5$ s			
		$d = 1.47Vt$	V = design speed (mi/h)	

Procedures for Determining Curve Advisory Speed Limits

3 $V = \sqrt{127R\left(lateral\_acc + superelevation\right)}$ 6-6

4.1 $SF = 1 + 0.03476V - 0.00004762V^{2}$

4.2 $V_{acc} = \sqrt{127R\left(\frac{lateral\_acc}{SF} + superelevation\right)}$

5.1 $SD_{acc} = 2R\cos^{-1}\left(\frac{R-O}{R}\right)$

5.2a $SD_{stop} = SD_{acc} = \frac{T_r V_{sight}}{3.6} + \frac{V_{sight}^{2}}{254d}$

5.2b $V_{sight} = 127d\left(-\frac{T_r}{3.6} + \sqrt{\left(\frac{T_r}{3.6}\right)^{2} + \frac{4SD_{acc}}{254d}}\right)$

Variables

R = Curve Radius (m)
O = Offset Distance from center of the lane to the obstruction (m)
T_r = Driver Reaction time (seconds)
d = Braking Coefficient
V = Vehicle Speed (km/h)
SD_{stop} = Stopping Sight Distance
SD_{acc} = Sight Distance
V_{acc} = Desirable maximum speed limited by lateral acceleration (km/h)
V_{sight} = Desirable maximum speed limited by sight distance (km/h)

Yellow Timing Interval Time Plus the Red Clearance Interval Time

Metric Values [English Values]: $\mathrm{CP} = \mathrm{t} + \frac{\mathrm{V}}{2\mathrm{a} + 2\mathrm{Gg}} + \frac{\mathrm{W} + \mathrm{L}}{\mathrm{V}}$ 11-6, 22-38

Metric:

a = deceleration, m/s^2 (typically 3.1 m/s^2)
G = gravity @ 9.8

English:

a = deceleration, ft/s^2 (typically 10 ft/s^2)
G = gravity @ 32.2

Where:

CP = non-dilemma change period (Change + Clearance Intervals)
t = perception-reaction time (nominally 1 s)
V = approach speed, m/s [ft/s]
g = percent grade (positive for upgrade, negative for downgrade)
a = deceleration, m/s^2 (typical 3.1 m/s^2) [ft/s^2 (typical 10 ft/s^2)]
W = width of intersection, curb to curb, m [ft]
L = length of vehicle, m (typical 6 m) [ft (typical 20 ft)]

Gate Delay and Gate Interval Times

Gate operation time = Gate delay + Gate interval time 14-8

$$\text{Gate delay } (s) = \left[t + \frac{v}{2(a + G \cdot g)} + \frac{D}{v} \right]$$

$$\text{Gate interval time } (s) = \left[\frac{1}{v}(W_{ght} + L) \right]$$

Where:

t = driver perception-reaction time (PRT, s)
v = approach speed (m/s)
a = deceleration rate on level pavement (m/s^2)
G = acceleration resulting from gravity (m/s^2)
g = grade of approach lanes (percent/100)
D = distance between stop bar and gates (m)
L = length of the vehicle (m)
W_{ght} = distance between entry and exit gates (m); for calculation see below

$$\text{For } \alpha \le 90°: \quad W_{ght} = \frac{W_t}{\sin\alpha} + \frac{2W_h}{\tan\alpha} + \frac{2W_g}{\sin\alpha}$$

$$\text{For } \alpha > 90°: \quad W_{ght} = \frac{W_t}{\sin(180-\alpha)} + \frac{2W_h}{\tan(180-\alpha)} + \frac{2W_g}{\sin(180-\alpha)}$$

Where:

W_{ght} = distance between entry and exit gates (m)
W_t = width of railroad track (m)
W_h = width of approaching lane of the highway (m)
W_g = distance from track edge to gate (m)
α = crossing angle (degrees)

Contrast Ratio (light-emitting CMS)

Optimal contrast ratio range = 8-12 19-4

Where:

$$Contrast\ \ ratio = \frac{Luminance_{max}}{Luminance_{min}}$$

$Luminance_{max}$ = luminance emitted by the area or element of greatest intensity (text)
$Luminance_{min}$ = luminance emitted by the area or element of least intensity (background)

Display Time for Phases of Dynamic Messages Signs

$$T(s) = \frac{Legibility\ Distance(ft)}{Traveling\ Speed(ft/s)} \qquad 19\text{-}10$$

Where:

T = total time available to read the message
x = number of information units in phase 1
y = number of information units in phase 2

$Time\ for\ phase\ 1\ (t_1) = 2x$

$Time\ for\ phase\ 2\ (t_2) = 2y$

B = blanking time between phases

$T \geq B + t_1 + t_2$

Luminance Contrast

$$Luminance\ contrast = \frac{L_{stripe} - L_{pavement}}{L_{pavement}} \qquad 20\text{-}10$$

Where:

L_{stripe} = the luminance of the pavement marking
$L_{pavement}$ = the luminance of the pavement

CIE Veiling Luminance Model

$$\frac{L_{veil}}{I_{glare}} = \frac{10}{\theta^3} + \left[\frac{5}{\theta^2}\right] \cdot \left[1 + \left(\frac{A}{62.5}\right)^4\right] \qquad 21\text{-}2$$

Where:

I_{glare} = luminous intensity of glare source
θ = glare angle
A = driver age

Sight Distance

$d_{SD} = kVt_{prt} + kVt_{man}$, where maneuver time is input or

$d_{SD} = kVt_{prt} + d_{manV}$, where maneuver distance is input 22-2

Where:

d = required sight distance
V = velocity of the vehicle(s)
t_{prt} = PRT
t_{man} = MT
d_{manV} = distance required to execute a maneuver at velocity V
k = a constant to convert the solution to the desired units (feet, meters)

Reading Time (Sign Comprehension)

$$\text{Reading time (seconds)} = 1(\text{number of symbols}) + 0.5(\text{number of words and numbers})$$ 22-32

Reading Distance (Sign Placement)

Base Reading Time (BRT): $\text{BRT (s)} = 0.5x + 1y$ 22-39

Where:

x = the number of critical words/numbers in the message
y = the number of critical symbols in the message

Reading Time (Complex Signs in High-Speed Conditions)

$$\text{Reading Time (s)} = 0.31\ (\text{Number of Familiar Words}) + 1.94$$ 22-40

Reading distance is obtained by multiplying the reading time by the travel speed

Information Presence Distance (Sign Placement)

$$\text{Information Presentation Distance} = \text{Reading Distance} + \text{Decision Distance} + \text{Maneuver Distance}$$ 22-41

Legibility Distance (Sign Placement)

$$\text{Legibility Distance} = \text{Information Presentation Distance} - \text{Advance Placement}$$ 22-41

Minimum Letter Height (Signs)

$$\text{Minimum Letter Height (in.)} = \frac{\text{Legibility Distance (ft)}}{\text{Legibility Index (ft/in.)}}$$ 22-41

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation