A Guidebook on Transit-Supportive Roadway Strategies (2016)

DETAILS

200 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-43110-1 | DOI 10.17226/21929

CONTRIBUTORS

Paul Ryus, Kelly Laustsen, Kelly Blume, Scott Beaird, and Susan Langdon; Transit Cooperative Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine. 2016. *A Guidebook on Transit-Supportive Roadway Strategies*. Washington, DC: The National Academies Press. https://doi.org/10.17226/21929.

TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 183

A Guidebook on Transit-Supportive Roadway Strategies

Paul Ryus
Kelly Laustsen
Kelly Blume
Scott Beaird
KITTELSON & ASSOCIATES, INC.
Reston, VA

Susan Langdon
SAVANT GROUP, INC.
Richardson, TX

Subject Areas
Pedestrians and Bicyclists • Public Transportation • Operations and Traffic Management

Research sponsored by the Federal Transit Administration in cooperation with the Transit Development Corporation

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2016
www.TRB.org

TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, adapt appropriate new technologies from other industries, and introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transportation Association (APTA), *Transportation 2000,* also recognized the need for local, problem-solving research. TCRP, modeled after the successful National Cooperative Highway Research Program (NCHRP), undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes various transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA; the National Academies of Sciences, Engineering, and Medicine, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel appointed by TRB. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired effect if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

TCRP provides a forum where transit agencies can cooperatively address common operational problems. TCRP results support and complement other ongoing transit research and training programs.

TCRP REPORT 183

Project A-39
ISSN 1073-4872
ISBN 978-0-309-37509-2

Published reports of the

TRANSIT COOPERATIVE RESEARCH PROGRAM

are available from

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet by going to

http://www.national-academies.org

and then searching for TRB

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Ralph J. Cicerone is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.national-academies.org**.

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

AUTHOR ACKNOWLEDGMENTS

This guidebook was developed under TCRP Project A-39. Paul Ryus of Kittelson & Associates, Inc. (KAI) was the Principal Investigator. Other authors of the report were Kelly Laustsen, Kelly Blume, and Scott Beaird of KAI and Susan Langdon of Savant Group, Inc.

Additional members of the research team were Zachary Bugg, Jon Crisafi, Alexandra Jahnle, Kevin Lee, Eric Lindstrom, Alex Skabardonis, and Tom Urbanik of KAI; Jennifer Butcher, Joshua Smith, and Omar Venzor of Savant Group, Inc.; and Brelend Gowan. Jackie Olsommer and Dorret Oosterhoff of KAI provided administrative assistance.

The researchers thank the organizations (listed in the contractor's final report, which is available as *TCRP Web-Only Document 66* at www.trb.org) and their staff members who took the time to participate in interviews during the course of the project.

FOREWORD

By Stephan A. Parker
Staff Officer
Transportation Research Board

TCRP Report 183: A Guidebook on Transit-Supportive Roadway Strategies (1) identifies consistent and uniform strategies to improve transportation network efficiency to reduce delay and improve reliability for transit operations on roadways; (2) develops decision-making guidance for operational planning and functional design of transit/traffic operations on roads that provides information on warrants, costs, and impacts of strategies; (3) identifies the components of model institutional structures and intergovernmental agreements for successful implementation; and (4) identifies potential changes to the *Manual on Uniform Traffic Control Devices* (MUTCD) and related documents to facilitate implementation of selected strategies. *TCRP Report 183* is a resource for transit and roadway agency staff seeking to improve bus speed and reliability on surface streets while addressing the needs of other roadway users, including motorists, bicyclists, and pedestrians.

TCRP Project A-39, "Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies," conducted an extensive review of transit-preferential treatments used in the United States and internationally, including information on when these treatments are applied and how they are designed. The researchers interviewed a number of transit and roadway agencies to identify lessons observed and effective practices from actual project implementations, with a particular focus on successful techniques for transit agencies, roadway agencies, and project stakeholders to work together toward outcomes that benefit all parties involved. The project presents findings from a series of gap-filling research efforts on (1) innovative international strategies not yet in common use in the United States; (2) a simulation study of the effects of stop location, transit signal priority, and queue jumps on bus and general traffic travel times and travel time variability; (3) an evaluation of selected strategies implemented in the Seattle area; and (4) identifying conditions when the delay benefit produced by a strategy at an upstream intersection is lost at the next downstream signal, resulting in no net benefit. Finally, the research report identifies possible changes to the next edition of AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets,* based on the findings of this project.

This project created three products that are available on the TRB website (www.TRB.org) by searching for "*TCRP Report 183*": (1) this guidebook, (2) a research report on the methodology used to develop the guidebook (*TCRP Web-Only Document 66*), and (3) a PowerPoint presentation describing the entire project.

CONTENTS

SUMMARY

A Guidebook on Transit-Supportive Roadway Strategies

TCRP Report 183: A Guidebook on Transit-Supportive Roadway Strategies is a resource for transit and roadway agency staff seeking to improve bus speed and reliability on surface streets while also addressing nearby land uses and the needs of motorists, bicyclists, and pedestrians. The guidebook:

- Discusses why improving bus speed and reliability is important for transit, roadway, and planning agencies, as well as the community at large;
- Provides guidance on planning and implementing a successful project, with particular attention to the coordination and communication needs of project stakeholders;
- Defines and describes 34 strategies for improving bus speed and reliability, including a range of transit operation, traffic control, infrastructure, and bus lane strategies;
- Provides guidance on selecting an appropriate strategy to address a particular cause of a bus speed or reliability problem; and
- Gives case study examples of how transit and roadway agencies have successfully worked together to implement these strategies.

Figure S-1 presents the structure of this guidebook. The guidebook is organized around several themes: fundamentals, laying the foundation for a successful project, selecting appropriate strategies, identifying the potential benefits of these strategies, and reference material. It is not necessary, or intended, that users read this guidebook from cover to cover. Instead, the majority of the guidebook provides information that will only be needed at specific points in the process of planning, designing, and implementing transit-supportive roadway strategies. The most important sections to read to get a good grounding on the topic are Chapters 1 through 3 and either Appendix A (for transit agency staff) or Appendix B (for transportation engineers and planners).

Chapter 1: Introduction defines a transit-supportive roadway strategy as any operational practice or infrastructure element that helps buses move more quickly along a street or route with more consistent travel times. It defines four categories of strategies—bus operations, traffic control, infrastructure, and bus lanes—and notes that many strategies provide a direct travel time or reliability benefit (or both), while some strategies help other strategies achieve their full potential.

Chapter 1 also describes the process used to develop this guidebook and notes that a companion report, *TCRP Web-Only Document 66: Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies* (which is available by searching for "*TCRP Web-Only Document 66*" at www.trb.org), describes the research effort behind the creation of this guidebook. Finally, Chapter 1 notes that this guidebook avoids the use of technical jargon when possible but provides definitions when technical terms are

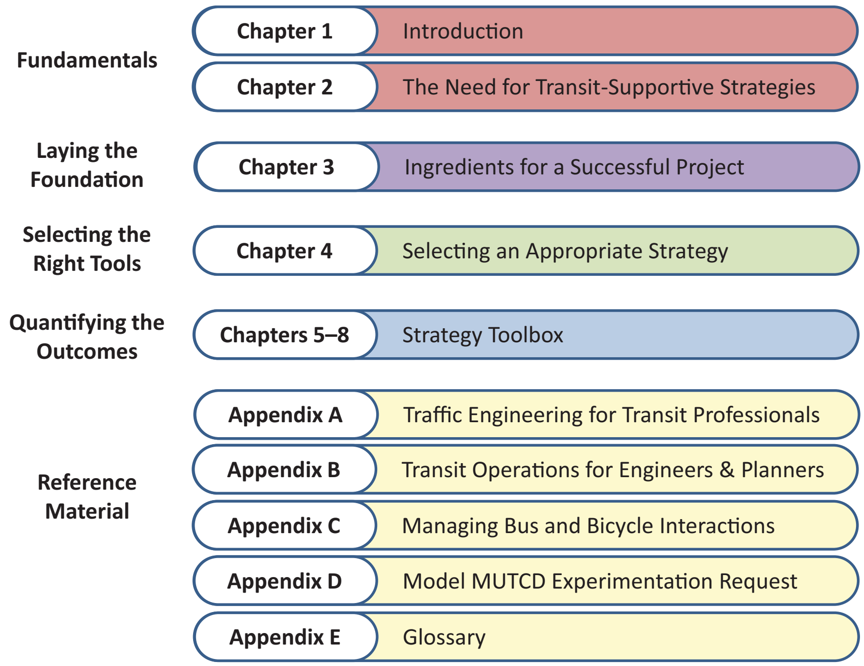


Figure S-1. Guidebook organization.

unavoidable. The chapter also introduces key resource documents that are suggested for use in conjunction with this guidebook.

Chapter 2: The Need for Transit-Supportive Roadway Strategies describes why improving bus speed and reliability is of interest to transit agencies, roadway agencies, planning agencies, and the community as a whole. It introduces the 34 strategies presented in this guidebook (shown in Figure S-2). The strategies are presented in order of increasing complexity to implement and are organized by category and in terms of required infrastructure, planning, analysis, operations, and stakeholder involvement. The chapter also defines each strategy and provides a photograph or graphic illustrating an application of the strategy. Finally, Chapter 2 presents four case studies of successful strategy implementations in the United States and internationally.

Chapter 3: Ingredients for a Successful Project describes a best practice for developing and implementing a transit-supportive roadway strategy (or package of strategies) and draws from the experiences of transit and roadway agencies that have successfully worked together to implement projects. While developing a project may be easier in some jurisdictions than in others, this chapter provides a pathway for making improvements regardless of the local policy environment and provides case study examples throughout that demonstrate how transit agencies have successfully applied each of the steps in the process. The chapter is organized around eight primary steps:

1. **Developing agency partnerships.** This is the most important step because almost all of the strategies identified in this guidebook require the participation of multiple agencies. Even when all of the participating parties are housed within the same governmental body (e.g., a city transit department, a city public works department, a city planning department), they often will have competing goals and objectives that will need to be reconciled. When agency staff understand their partners' needs, it leads to more successful outcomes and better working relationships on future projects. A formal interagency working group is always desirable and becomes increasingly essential as the complexity of a project increases.

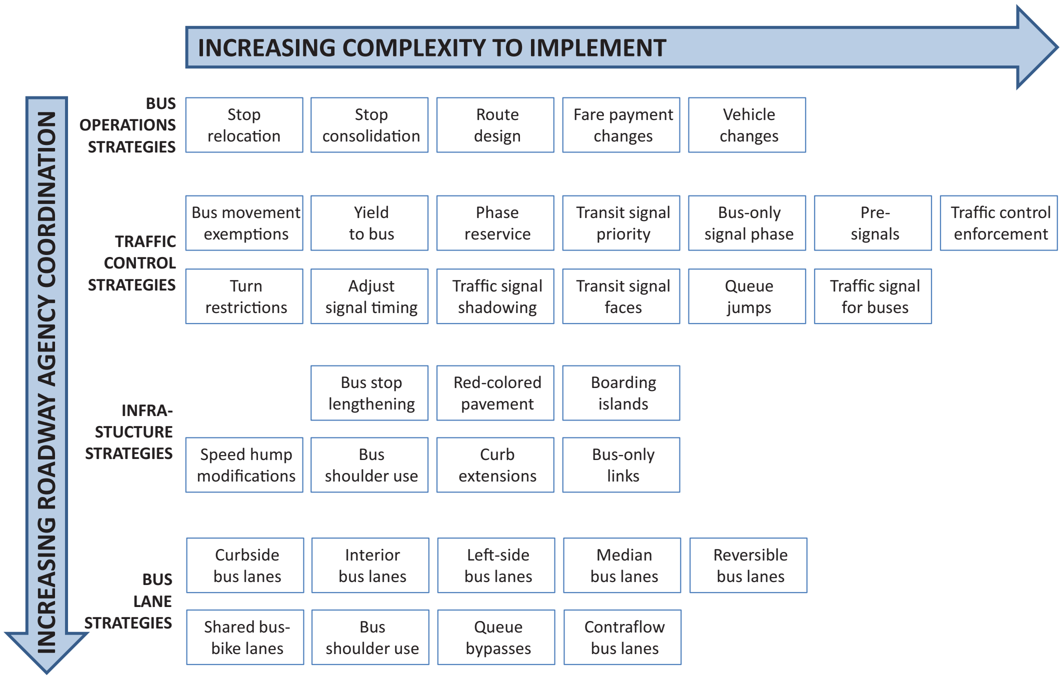


Figure S-2. Transit-supportive roadway strategies presented in this guidebook.

2. **Working within the policy environment.** Some jurisdictions are more open to transit-supportive roadway strategies than others. This guidebook presents a range of strategies applicable to different policy environments, whether they are strongly auto-focused, very transit-supportive, or somewhere in between. Successful first projects can help improve the policy environment for future projects.
3. **Problem identification and strategy development.** The transit agency should ask itself what the problem is that needs to be solved, determine whether transit-supportive roadway strategies are the best approach to solving the problem, and if so, identify potential strategies to evaluate. Typical sources of problems that can be addressed by the strategies in this guidebook are traffic congestion, traffic signal delays, poorly connected street networks, increased passenger demand, and the number and location of bus stops. Problems requiring a different approach include long-term road construction, buses breaking down while in service, inadequate bus and operator availability, insufficient time allocated in the schedule, differences in operator driving skills and route familiarity, and environmental conditions (e.g., rain, snow).
4. **Working within the regulatory environment.** Transportation engineers typically work with three types of documents:
   a. **Standards,** which provide no room for variation and interpretation, except that provided through a formal exception process;
   b. **Guidance,** essentially a recommendation on best practice, with room for interpretation; and
   c. **State or local practice,** which is the way individual roadway agencies implement standards and guidance.

   Transit-supportive roadway strategies are still an emerging area of traffic engineering practice and are not fully accounted for in current standards, guidance, or practices. Therefore, particularly the first time a particular strategy is used in a community, there is often a need to identify constraints and either work within them or look for opportunities to modify them.

5. **Engaging project stakeholders.** No matter the size of the project, there will likely be a need for the transit agency to engage stakeholders beyond just the roadway agency. For a bus stop relocation, this may simply involve the adjacent property owner(s). For a large corridor project (e.g., a bus rapid transit route incorporating bus lanes and other strategies), an extensive stakeholder engagement effort will likely be needed. Potential stakeholders include a range of public agencies, community organizations, institutions, individuals, business and property owners, and nonprofit organizations.
6. **Implementing the project.** It is a good idea to establish memoranda of understanding or interagency agreements that specify the role of each partner agency in planning, funding, designing, constructing, operating, or maintaining the project. In addition, a common theme from the transit and roadway agency interviews conducted during the development of this guidebook was to not underestimate the time required to take a project from the planning stage to opening day. It is suggested to establish adequate milestones with expected outcomes and to build contingencies into the schedule to address challenges that arise during the course of the project.
7. **Quantifying the results.** An often-overlooked step is to quantify the project's outcomes, but this step is important for identifying improvements in the way the strategy is applied, to build support for implementing the strategy again in the future, and to improve the transit industry's knowledge of the benefits of particular strategies.
8. **Building on success.** Once the project is complete, it is important to consider other opportunities to build on the project's success. The interviews conducted for this guidebook indicated that although roadway agencies may initially be hesitant to pursue transit-supportive roadway strategies due to concerns about automobile operations, they often become more open to implementing more strategies when they have a positive first experience with a strategy.

Chapter 4: Selecting an Appropriate Strategy describes potential methods for selecting and evaluating strategies, provides guidance on specific strategies that can address particular bus operations problems, and provides a summary table that highlights the key applications, benefits, costs, and constraints of the strategies presented in this guidebook. In particular, the traditional approach of using warrants based on minimum bus volumes to justify the implementation of transit-supportive roadway strategies is contrasted with the current evolution of traffic engineering practice toward more flexible approaches to solving problems by considering a variety of factors and stakeholder needs.

Chapters 5 through 8, the strategy toolbox chapters, make up the majority of this guidebook and provide detailed descriptions of each of the strategies addressed. The information provided for each strategy includes definition, purpose, potential applications, other strategies that can be implemented in combination with the strategy, potential constraints that could prevent the strategy from being applied, potential benefits for the transit agency and other project stakeholders, cost considerations, implementation examples, implementation guidance, and references to other relevant documents. Illustrations and photographs are provided when relevant.

Five appendices provide supplemental information:

- **Appendix A: Understanding Traffic Engineering Practice (for Transit Professionals)** is designed to provide transit professionals a description of the traffic engineering profession as it relates to implementing transit-supportive roadway strategies. It covers the use of traffic engineering standards, describes reference documents and analysis tools commonly applied by traffic engineers, and provides a primer on how traffic signals operate and how transit operations can be integrated into traffic signal operation.

- **Appendix B: Understanding Transit Operations (for Transportation Engineers and Planners)** is designed to provide transportation engineers and planners a description of transit operations, how transit-supportive roadway strategies can help improve transit operations, and why improving operations is an important goal of transit agencies. It contrasts the service-oriented nature of transit operations to the facility-oriented nature of roadways, presents basic bus scheduling concepts that illustrate the direct relationship between bus speeds and a route's operating costs, and describes transit-specific performance measures and reference documents.
- **Appendix C: Managing Bus and Bicycle Interactions** provides guidance on potential solutions for accommodating both bicycles and buses on streets and at bus stops. Even though bicycle facilities are not necessarily transit-supportive roadway strategies, not considering bicyclist needs may result in a strategy that cannot be implemented.
- **Appendix D: Request to Experiment Template** provides a model *Manual on Uniform Traffic Control Devices* (MUTCD) experimentation request for using red-colored pavement on bus-only lanes and links. The model is for use until such time that this strategy is incorporated into the MUTCD or is addressed by an Interim Approval issued by the Federal Highway Administration.
- **Appendix E: Glossary** provides definitions of transit and traffic engineering terms used in this guidebook.

CHAPTER 1

Introduction

Improving bus travel times and travel time reliability are key considerations for transit agencies because these issues directly affect the cost of providing service, and good performance in these areas is important for attracting new riders and retaining existing riders. They are also important considerations for planning agencies since attractive transit service helps support local and regional goals to provide multimodal mobility choices for all segments of the population, to create more-sustainable communities, and to support land use development efforts in central business districts and other activity centers. Finally, they are important considerations for roadway agencies, which are increasingly faced with the need to use limited roadway space as efficiently as possible since improved transit service can greatly increase the number of people served by a roadway without requiring the need for expensive widening.

This guidebook provides numerous examples of transit-supportive roadway strategies that can be used to improve transit speed and reliability on urban and suburban streets. Although the guidebook focuses on the bus mode (including bus rapid transit [BRT] and commuter bus service), many of the strategies presented here are also potentially applicable to demand-responsive transit, streetcars, and portions of light rail transit systems operating on-street. Bus facilities on freeways, bus-only streets, and off-street bus facilities are outside the scope of this guidebook.

Successful transit-supportive roadway projects require the active participation of both transit and roadway agencies, along with the involvement and support of external stakeholders who may benefit from, or potentially be affected by, these projects. Consequently, this guidebook also presents best practices for developing interagency cooperation and provides examples of successful partnerships.

Finally, a key to developing working agency partnerships is understanding a partner agency's needs and constraints. Because most transit agency staff are not transportation engineers and most transportation engineers and planners have not worked in transit agencies, this guidebook also explains basic concepts and terms used by each group in order to help them understand each other.

1.1 What Is a Transit-Supportive Roadway Strategy?

A transit-supportive roadway strategy is any operational practice or infrastructure element that helps buses move more quickly along a street or route with more consistent travel times. This guidebook defines the following main categories of strategies:

- **Bus operations strategies.** Changes made by the transit agency in the way it provides service, such as relocating bus stops, consolidating bus stops, and changing the way fares are paid.
- **Traffic control strategies.** Changes to the way traffic is regulated that are for the benefit of transit; examples include changing traffic signal operations to prioritize bus movements and

changes to traffic regulations to improve traffic flow generally or bus movements specifically (e.g., prohibiting left turns where no left-turn lane is provided, or exempting buses from right-turn-only requirements).

- **Infrastructure and bus lane strategies.** Changes to physical elements of the roadway, such as extending sidewalk space into the parking lane (curb extensions) or constructing bus lanes. Because of the wide variety of bus lane types, this guidebook discusses them separately from other infrastructure strategies.

Some strategies can also be thought of as support strategies—that is, strategies that do not necessarily provide a bus travel time benefit on their own but help another strategy achieve its maximum effectiveness. Examples include red-colored pavement in bus lanes (to improve the lanes' conspicuity and deter inadvertent bus lane violations), traffic enforcement (to ensure that bus-only facilities are not used by other vehicles), and special traffic signal displays for buses (to reduce potential motorist confusion if standard red/yellow/green signal displays were to be used to control bus-only movements).

Finally, many strategies lend themselves to being implemented as part of a package of strategies where multiple strategies are implemented at the same time (e.g., a combination of stop consolidation, curb extensions, and transit signal priority along a bus route). This approach helps combine the individual travel time benefits from specific strategies into a larger benefit that may be more noticeable to passengers and more useful to the transit agency in terms of scheduling flexibility.

1.2 How to Use This Guidebook

This guidebook is written for transit and roadway agency staff who are looking for ways to improve bus operations on city streets or who are being asked to consider proposals to implement a specific strategy.

For transit agency staff, this guidebook provides detailed information about the range of strategies that are available to address specific operating issues that a bus route (or bus service along a street) may be facing. This information includes descriptions of each strategy, potential strategy applications and constraints, typical benefits, relative costs, and specific implementation guidance. The guidebook also describes what kind of information a roadway agency will likely want to see when considering a proposal, as well as common standards, policies, and guidelines that roadway agencies follow when planning and implementing roadway projects.

For roadway agency staff, the guidebook provides examples of cities where specific strategies have been successfully applied, references to national documents such as the *Manual on Uniform Traffic Control Devices* (MUTCD, FHWA 2009) and various AASHTO publications that provide guidance on these strategies, and information on the likely impact of strategies on roadway users (including bicyclists and pedestrians) and other stakeholders. The guidebook also suggests methods for fairly evaluating proposed transit-supportive roadway strategies and describes why applying these strategies is important for transit agencies.

For all readers, the guidebook provides examples of interagency partnerships that have resulted in successful implementations of transit-supportive roadway strategies.

This guidebook is not intended to be read cover to cover. Instead, the majority of the guidebook provides information that will only be needed at specific points in the process of planning, designing, and implementing transit-supportive roadway strategies. The most important sections to read to get a good grounding on the topic are those in Chapters 1 through 3 and either Appendix A (for transit agency staff) or Appendix B (for transportation engineers and planners).

The guidebook contains eight chapters. In addition to this introductory chapter:

- Chapter 2 describes why transit-supportive roadway strategies are needed and introduces the range of strategies covered by the guidebook.
- Chapter 3 provides guidance on developing successful interagency partnerships and successful projects.
- Chapter 4 provides a process for selecting an appropriate strategy.
- Chapters 5 through 8 present a toolbox of potential strategies that are organized by bus operations strategies, traffic control strategies, (non–bus lane) infrastructure strategies, and bus lane strategies.

In addition, references and the following five appendices are provided:

- Appendix A is written for transit agency staff and provides a primer on traffic engineering concepts and reference documents that apply to transit-supportive roadway strategies.
- Appendix B is written for roadway agency staff and provides a primer on transit operations concepts and reference documents that apply to transit-supportive roadway strategies.
- Appendix C provides guidance on managing bus and bicycle interactions in bus lanes and at bus stops.
- Appendix D contains a template for submitting an experimentation request to the FHWA to use red-colored pavement for bus lanes and other bus-only links.
- Appendix E is a glossary of terms used in this guidebook.

1.3 How This Guidebook Was Developed

This guidebook was developed under TCRP Project A-39, "Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies." The project included an international literature review on transit-supportive roadway strategy implementations and guidance, interviews with transit and roadway agencies about successful projects implementing these strategies, and original research to fill gaps in knowledge on the impacts of specific strategies. This research is documented in a companion report, *TCRP Web-Only Document 66*.

1.4 Terminology

This guidebook avoids the use of technical terminology as much as possible. When use of a transit- or transportation engineering–specific term is unavoidable, it is defined the first time it is used in the text. Readers should note that transit industry terminology suffers from a lack of standardization; therefore, although the guidebook selects particular terms to use consistently throughout (e.g., *curb extension*), alternative terminology that may be more familiar to some readers is also provided (e.g., *bus bulb, bus nub*). Definitions of the different transit-supportive roadway strategies presented in the guidebook are provided in Section 2.2 and the Chapter 5 through 8 toolbox sections describing individual strategies. Appendix E provides a glossary of terms used.

1.5 Additional Resources

This guidebook's focus is on the planning, strategy selection, and implementation aspects of transit-supportive roadway strategies. It is designed to be used in combination with other reference documents that (1) describe specific design details for particular strategies and (2) provide methods for analyzing the potential benefits of a strategy in the unique context of a particular site. Documents that are frequently referenced within this guidebook include:

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (referred to as the Transit Guide, AASHTO 2014). This document provides specific design guidance (e.g., lane widths) for many of the infrastructure and bus lane strategies described in this guidebook. Chapter 4 of TCRP Project A-39's final report (*TCRP Web-Only Document 66*) provides possible changes to the AASHTO Transit Guide resulting from the research conducted.
- *Highway Capacity Manual 2010* (Transportation Research Board 2010). This reference is commonly used by transportation engineers to evaluate roadway operations and defines performance measures commonly used to evaluate those operations.
- *Manual on Uniform Traffic Control Devices* (FHWA 2009). The MUTCD is the national standard for traffic control devices such as road signs, traffic signals, and pavement markings. It is used in conjunction with state supplements that may prohibit specific options allowed by the national document.
- *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition (TCQSM; Kittelson & Associates et al. 2013). Chapter 6 of the TCQSM provides methods for estimating the effects of various strategies on bus delay and travel speed.
- *NCHRP Report 812: Signal Timing Manual*, 2nd Edition (Urbanik et al. 2015). This manual presents traffic signal and signal timing concepts, provides guidance on developing signal timing plans, and describes tools for timing signals and estimating the impacts of signal timing plans.

In addition, it will be necessary to check whether local and state design manuals and traffic laws currently permit a particular strategy. If they do not, then work will be needed to obtain design exceptions or to change the relevant laws or standards prior to proceeding with that strategy. The strategy write-ups in the toolbox chapters (Chapters 5 through 8) indicate when a particular strategy is often subject to these constraints. The Additional Resources sections provided with each strategy write-up in the toolbox chapters list other strategy-specific resources that may also be useful.

Finally, two TCRP syntheses provide additional case study examples of successful implementations of transit-supportive roadway strategies: *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic* (Danaher 2010) and *TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds* (Boyle 2013).

CHAPTER 2

The Need for Transit-Supportive Roadway Strategies

As stated in the introduction, improving bus speed and reliability is of interest to transit agencies, roadway agencies, planning agencies, and the community as a whole. This chapter discusses why transit-supportive roadway strategies that improve bus speed and reliability are so vital, introduces and defines the range of strategies presented in the guidebook, and presents four examples of successful strategy implementations.

2.1 Challenges Faced by Transit Agencies

Transit agencies face a number of challenges to providing attractive, reliable, and cost-effective service. Three key challenges are discussed in the following subsections; additional details are provided in Appendix B.

Minimizing Operating Costs

As with any other kind of public agency, transit agencies are constantly challenged to do more with limited resources. In 2012, operating costs accounted for about 81% of a typical bus operator's total expenses. (Capital expenses such as buses, facilities, and transit infrastructure formed the remainder.) Vehicle operations and maintenance accounted for about 71% of the operating budget (APTA 2014). Consequently, anything that can be done to lower operating costs or to offset increases in other aspects of operating costs will have a direct impact on a transit agency's bottom line. Two of the important factors that influence bus operating costs are:

- **Headways.** The more frequent the service on a route, the higher the operating cost for the route since, all else being equal, more buses and drivers are needed to provide more frequency.
- **Route cycle time.** The longer the cycle time (the time required for a bus to make a round trip on a route, including the driver break or layover between trips), the more buses that are required to serve the route at a given headway. Cycle time is affected both by how fast buses can travel the route and by the variability of travel times from one trip to the next since the schedule needs to provide schedule recovery time to allow late-arriving buses to begin their next trip on time.

Actions that improve bus speeds or reduce travel time variability allow a route's cycle time to be reduced and thereby offer the potential to affect the route's operating costs. Depending on the magnitude of the cycle time reduction, one of the following can occur:

- Ideally, the cycle time is reduced sufficiently that a bus can be saved on the route (i.e., the same headway can be offered with one fewer bus). Because the required cycle time reduction will often be slightly less than the headway for an efficiently scheduled route, this result is more likely to occur when headways are short. The savings can be used for higher-frequency service on the route (i.e., shorter headways using the same number of buses), a longer span of service, service improvements elsewhere in the system, or to help offset increased costs in other areas.

- More typically, the cycle time is reduced somewhat, but not enough to save a bus. This can still be a valuable outcome since it means that a buffer of time has been provided that postpones the need for adding a bus to the route (e.g., in response to slower travel times due to increased traffic congestion or increased passenger demand). Therefore, it delays a major increase in the route's operating costs—potentially many years into the future (Koonce et al. 2006). Alternatively, the route can be extended to serve a greater area within the same amount of time.

Attracting Ridership

Building transit ridership is important to many transit stakeholders. From the transit agency's perspective, increases in ridership are an indicator of agency success in fulfilling its mission to provide transportation options to the public. New ridership also brings in new fare revenue, and ridership is a component of some formulas used to allocate grant funding to transit agencies, both of which allow transit agencies to provide a better quality of service, which in turn attracts even more passengers.

From a roadway agency's perspective, shifting trips from the automobile mode to the transit mode makes the roadway system operate better for all road users and postpones the need for costly road expansion, assuming expansion is even possible. From the community's perspective, allowing transit to operate as efficiently as possible on the roadway system preserves and enhances the community's investment in transit service, allowing funds to be spent on service quality improvements rather than on adding buses to maintain headways when buses are faced with increased traffic congestion.

Ridership tends to improve by 0.3% to 0.5% for every 1% reduction in travel time (Kittelson & Associates et al. 2007). Travel time variability improvements discussed in the literature have had little or no documented impact on ridership, although some positive impact might be expected, and passengers have been shown to perceive unexpected waiting time as being 2 to 5 times more onerous than in-vehicle travel time (Kittelson & Associates et al. 2013).

Increased Roadway Congestion

Increased roadway congestion is a challenge to transit service in several ways. Traffic congestion slows travel times and creates travel times that are more variable. Slower travel times, in turn, require transit agencies to use more buses to maintain headways, which increases operating and maintenance costs. Transit-supportive roadway strategies can help postpone the need to add buses to a route to maintain headways, which can result in substantial avoided costs. For example, the TriMet (Portland, Oregon) Streamlining program postponed the need to add buses to 12 routes by approximately 8 years, avoiding approximately $13.4 million in operating costs over that time and also postponing the need for capital expenditures for new buses for those routes (Koonce et al. 2006).

2.2 Types of Strategies

This section introduces and defines the transit-supportive roadway strategies described in the guidebook. The strategies are divided into four categories that describe the general way the strategy acts to improve bus speeds and reliability. The order of the categories also generally reflects an increasing need for a transit agency to coordinate with different organizational elements within a roadway agency. The four categories of strategies are:

1. **Bus operations.** These are strategies that a transit agency can implement on its own with minimal roadway agency involvement beyond that normally required when moving or installing bus stops.

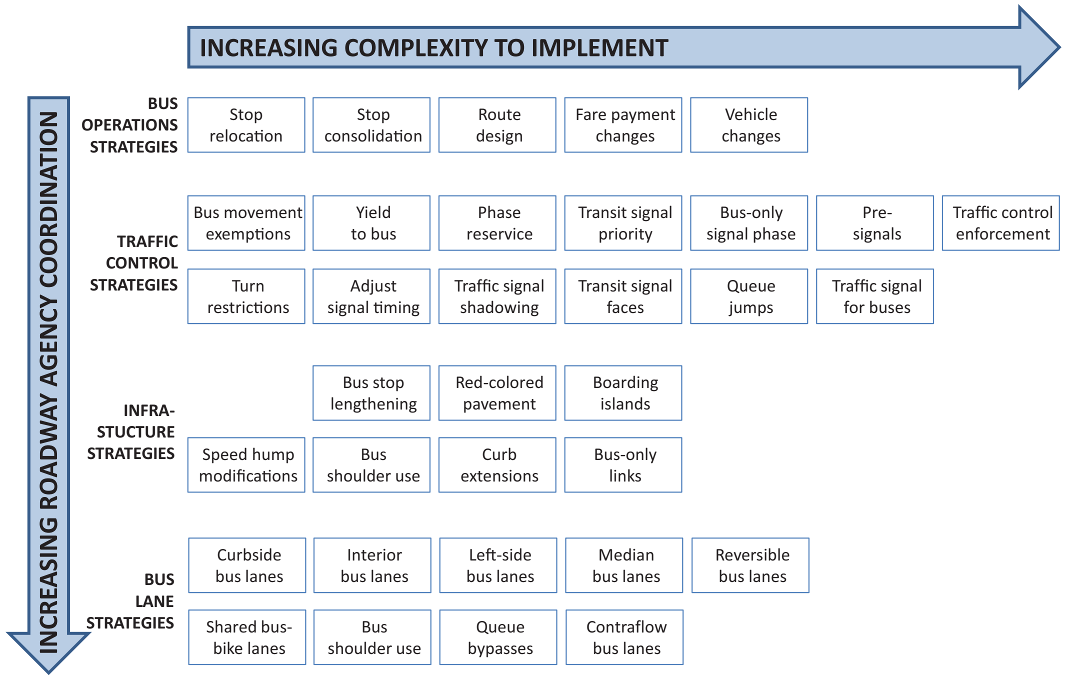


Figure 1. Transit-supportive roadway strategies categorized.

2. **Traffic control.** Strategies that affect signal timing, phasing, and indications; change existing traffic regulations or laws to prioritize bus movements; and enforce traffic regulations.
3. **Infrastructure.** Physical improvements to the roadway, other than bus lanes, designed to directly improve bus speed or reliability or that support other strategies for doing so.
4. **Bus lanes.** Travel lanes dedicated exclusively or primarily for bus use.

Figure 1 shows the 34 transit-supportive strategies presented in this guidebook. They are organized by category and in order of increasing complexity to implement in terms of required infrastructure, planning, analysis, and stakeholder involvement.

Table 1 through Table 4 define and illustrate the strategies included in each of these categories. The toolbox chapters of the guidebook, Chapters 5 through 8, provide detailed descriptions of each strategy; the tables provide the section number within these chapters where a given strategy is covered.

2.3 Success Stories

This section provides four examples of different approaches to implementing transit-supportive roadway strategies that resulted in successful outcomes, either in the United States or internationally. Additional U.S. and Canadian case study examples are provided in Chapter 3, and more details are provided in Appendix B of the TCRP Project A-39 final report (available as *TCRP Web-Only Document 66*).

King County, Washington

King County Metro operates a form of BRT branded as RapidRide. At the time of the interview with King Country Metro, the service provided frequent trips throughout the day on four lines, with two additional lines planned for service in 2014. RapidRide service was launched in 2010,

(continued on p. 17)

Table 1. Bus operations strategies in Chapter 5.

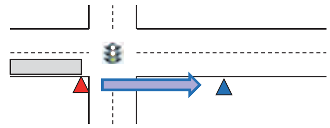
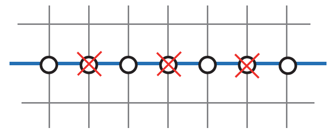
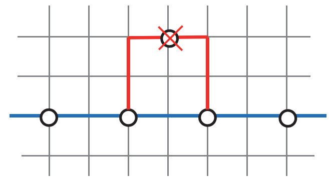
Strategy (Section)	Description	Illustration
Stop relocation (5.1)	An existing bus stop is moved from its current location at an intersection (e.g., near side) to a different location (e.g., far side).	
Stop consolidation (5.2)	Bus stop spacing is optimized—typically by increasing the bus stop spacing—so that buses make fewer stops along the route, while minimally affecting the area served by transit.	
Route design (5.3)	A route's alignment is adjusted to provide a faster, more direct trip from origin to destination for the majority of passengers.	
Fare payment changes (5.4)	Changes are made in how or where bus fares are paid (or both), with the intent of reducing the time required to pay fares. Some types of fare payment changes are implemented in conjunction with all-door boarding, which further speeds up the boarding process.	
Vehicle or equipment changes (5.5)	The type of bus used on a route, or the equipment used on a bus, is changed to allow passengers to board and alight faster, to provide improved interior circulation, to improve vehicle performance, to allow more-direct routings, or a combination of these.	

Table 2. Traffic control strategies in Chapter 6.

Strategy (Section)	Description	Illustration
Movement restriction exemption (6.1)	Buses are allowed to make movements (e.g., left turn, right turn, proceed straight ahead) that are prohibited to other vehicles.	...EXCEPT BUS...
Turn restrictions (6.2)	One or more existing general traffic turning movements at an intersection are prohibited.	
Yield to bus (6.3)	Motorists are required by law, or are encouraged through bus-mounted signs, to let buses back into traffic when they are signaling to exit a bus stop.	

(continued on next page)

Table 2. (Continued).

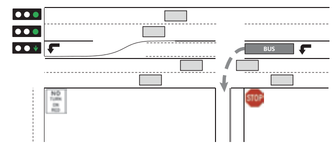
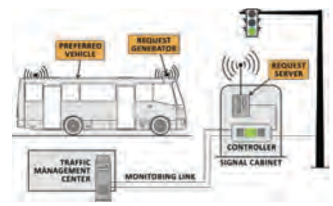
Strategy (Section)	Description	Illustration
Passive traffic signal timing adjustments (6.4)	Existing signal timing plans are optimized to reduce delay for traffic in general on the intersection approaches used by buses, or for buses specifically. Since the signal timing is followed whether or not a bus is present, the adjustments are considered to be passive.	
Phase reservice (6.5)	A traffic signal phase is served twice during a traffic signal cycle—for example, a left-turn phase that is served both at the start and the end of the green phase for through traffic.	
Traffic signal shadowing (6.6)	A bus wishing to turn left at an unsignalized intersection triggers a call for a left-turn phase at a nearby downstream intersection, thereby creating a gap in traffic that the bus can use to turn left.	
Transit signal priority (6.7)	Traffic signal timing is altered in response to a request from a bus, so that the bus experiences no or reduced delay passing through the intersection.	
Transit signal faces (6.8)	Special traffic signal faces (displays) used for controlling bus, streetcar, or light rail operations.	
Bus-only signal phase (6.9)	A traffic signal phase included in the traffic signal cycle to serve bus movements that cannot be served, or are not desired to be served, concurrently with other traffic.	
Queue jumps (6.10)	Buses (or in some applications, buses and right-turning vehicles) are provided an opportunity to move ahead of queued through-vehicles at a signalized intersection and, in many cases, to proceed into the intersection in advance of the through traffic.	
Pre-signals (6.11)	A traffic signal for one direction of a street, coordinated with a traffic signal at a downstream intersection, that is used to control the times when particular vehicles may approach the intersection.	
Traffic signal installed specifically for buses (6.12)	An intersection that is signalized primarily to serve bus movements rather than general traffic.	
Traffic control enforcement (6.13)	Automated or manual techniques to enforce traffic laws essential for the successful operation of transit-supportive roadway strategies.	

Table 3. Infrastructure strategies in Chapter 7.

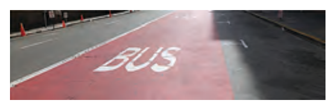
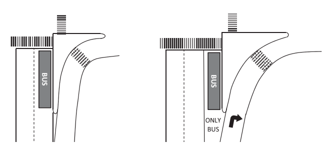
Strategy (Section)	Description	Illustration
Speed hump modifications (7.1)	Speed bumps and humps along bus routes are replaced with bus-friendlier versions.	
Bus stop lengthening (7.2)	A bus stop's length is increased to allow it to serve more (or longer) buses simultaneously.	
Bus shoulder use (7.3)	Buses are allowed to use roadway shoulders during peak periods.	
Red-colored pavement (7.4)	All, or selected segments, of a bus lane are indicated with red-colored pavement as a supplement to the normal bus lane signing and striping.	
Curb extensions (7.5)	Curb extensions (bus bulbs, bus nubs) extend the curb and sidewalk out to the edge of the parking lane.	
Boarding islands (7.6)	Bus stops on raised concrete islands within the roadway.	
Bus-only links (7.7)	Bus-only links (bus gates, bus-only crossings, bus sluices) are short sections of roadway connecting public streets that can only be used by transit vehicles and other authorized vehicles (e.g., emergency vehicles).	

Table 4. Bus lane strategies in Chapter 8.

Strategy (Section)	Description	Illustration
Bus lane, generally (8.1)	A roadway lane dedicated exclusively or primarily for the use of buses.	
Curbside bus lane (8.2)	A bus lane located in the rightmost lane of the roadway, adjacent to the right curb.	
Shared bus and bicycle lane (8.3)	A curbside lane shared part- or full-time by buses and bicycles; other users may also be allowed into the lane at specific times or locations.	
Interior (offset) bus lane (8.4)	A bus lane in the interior of the roadway, typically located to the left of the curb (parking) lane but can also be another non-curb lane.	
Left-side bus lane (8.5)	A bus lane on the left side of the roadway, adjacent to the left curb or parking lane on one-way streets, or adjacent to the median on two-way streets.	
Queue bypass (8.6)	A relatively short bus lane that allows buses to move to the front of the line at a bottleneck, where they then merge into the adjacent general traffic lane.	
Median bus lanes (8.7)	Lanes reserved for the exclusive use of buses, located in the middle of a roadway and often separated from other traffic by curbs or landscaped islands.	
Contraflow bus lane (8.8)	A bus lane provided in the opposite direction of normal traffic flow on a one-way or divided street.	
Reversible bus lane (8.9)	A single bus lane that serves buses operating in both directions.	

(continued from p. 12)

using high-capacity, low-emission hybrid buses and distinctive branding to distinguish its service. Buses are scheduled by headway, rather than according to a fixed timetable, and provide 10-min headways during the morning and evening peak and 15-min service during off-peak periods.

The RapidRide program was developed by King County Metro after several years of reviewing and studying BRT services around the country and world. Managers traveled to different transit forums and agencies to assess how different groups were implementing BRT and considered how a similar service could be applied within King County. Metro spent several years developing a transit package, which included funding avenues, branding the service, selecting BRT elements, and identifying potential bus lines. RapidRide was one of the main features of the transit package. The transit improvements are primarily funded through a 0.1% sales tax increase approved by King County voters in 2006 as part of the Transit Now initiative to expand transit service.

Project partnerships included the cities of Seattle, Bellevue, Redmond, Tukwila, Burien, SeaTac, Des Moines, Kent, Federal Way, Renton, and Shoreline. All partners were involved in discussions on conceptual-level improvements and route alignment. These partners, along with the Washington State Department of Transportation (DOT), share fiber-optic lines along RapidRide corridors.

A set of speed and reliability partnerships were developed for the RapidRide project. The partnerships were contractual, formal interagency agreements that detailed certain infrastructure improvements that a city would provide in exchange for increased transit service operating hours. In the beginning, King County Metro worked to develop the initial agreements and negotiated the details of the partnerships with partner agencies. At times, the agreements were subsequently amended based on community feedback and technical feasibility issues. Infrastructure operations and maintenance details also had to be negotiated.

Metro worked with local agencies to assess what they could implement, given right-of-way (ROW) and other factors. Through the Speed and Reliability Partnership program, local agencies also proactively looked at what they could do to improve transit. This coordination helped Metro and partnership agencies streamline the process to develop transit packages with the best ideas possible. As more transit corridors have been identified and developed, Metro has tried to develop standard practices for RapidRide corridors.

King County Metro held a wide variety of meetings with stakeholders throughout the stages of each of the corridor projects. The meetings were identified and held on a case-by-case basis, with some corridor projects having only a few meetings, and the higher-profile projects requiring additional meetings.

In the beginning, agency partners had concerns about BRT's impacts on general traffic and pedestrian operations. The King County Metro staff members heading up the speed and reliability projects were all traffic engineers, so they had a good understanding of traffic operations and terminology. Some agencies had difficulty understanding the operational impact of transit signal priority (TSP). In particular, thinking about the bus route as a whole was a new concept for city staff. They needed help to realize that if, for example, reliability improvements were made along one portion of a route, then riders boarding further along the route would benefit. In addition, there would be potential reduced operating costs due to less recovery time needed.

Significant progress was made with the City of Seattle when one of the operations engineers took the initiative to try out the full transit priority operation (with phase skipping) for a week at a moderately congested intersection during the a.m. and p.m. peak periods. This test allowed city staff to become comfortable with the TSP operation, observe impacts to pedestrians, and recognize that the overall trade-offs to the vehicular and pedestrian operations were acceptable. As a result, this engineer became a champion for the concept. Finding a champion at other agencies

18 A Guidebook on Transit-Supportive Roadway Strategies

was more challenging. With the smaller cities, a key element to the success of the project was loaning them spare TSP hardware that they could experiment with in their signal shops.

Additional challenges included right-of-way conflicts between the transit speed and reliability improvements, the Seattle Bike Master Plan, and Seattle Freight Master Plan. In some cases, there were incompatible plans proposed for the RapidRide corridors in these other master plans, which generated additional hurdles and negotiations during design phases.

Spokane, Washington

The Spokane Transit Authority (STA) worked with stakeholders, including internal staff from multiple departments, several local jurisdictions, and the general public, on a bus stop consolidation project. The stakeholders started their involvement in the project at varying places in the project's development. The STA Planning Department was involved during the initial phase of the project. The STA Service Improvement Committee was shown initial drafts of the project and assisted in refining the project scope. The STA Facilities and Grounds Department was involved after the draft plan was developed; since the department was responsible for removing bus stop signs, it provided input on the project scope. Fixed-route bus operators were involved during the draft phase, when they were provided information and maps for review and comment. The general public was involved during the draft phase, when information was provided via web reports, online surveys, and signs posted at bus stops that were planned to be closed. Local jurisdictions became involved during the final draft phase, when they were provided information on locations and timelines for removals.

Various levels of meetings were held during the project for information dissemination and project planning. The Planning Department held meetings to discuss the project and gather input. The Service Improvement Committee held regular biweekly meetings during project development, and bus stop consolidation projects were added to the agenda for these meetings regularly during the initial planning phase of the project as well as later when discussion items warranted it. The Facilities and Grounds Department met to discuss the scope and estimated schedule and to provide input on what its staff could accomplish for physical removal of bus stop signs. Fixed-route operators were provided with draft location maps for review and comment. STA staff were available to meet with operators to discuss the project and address concerns. No public meetings were held.

One internal hurdle to overcome was that a small minority of the fixed-route operators felt the stop consolidation project was detrimental to the public. However, after the first phase of the project was completed, the fixed-route operators began to see that removing stops did in fact improve bus speed and reliability, which was a real breakthrough moment. The lesson learned by STA was that it is important that internal agency groups understand the project and the need for it. They may not agree with the project concept, but if they are armed with the correct information, the public receives a consistent message from all departments. This is especially true for the bus operators since they are the face of the agency and often the first point of contact for a customer with a question.

Ottawa, Canada

OC Transpo, a department of the City of Ottawa, provides transportation service throughout the Ontario portion of the National Capital Region. In the past, this region consisted of local municipalities and a regional government, but it has since been consolidated into a single entity, the City of Ottawa. Major highways in the region are owned by the Ontario Ministry of Transportation, while the National Capital Commission owns some scenic parkways that are part of longer-distance bus routes. Within the city governmental structure, OC Transpo interacts with two offices within public works (traffic operations, and traffic safety and signs), as well as with the pedestrian and bicycle office within the planning department.

Ottawa is known for its off-street, grade-separated Transitway; however, many other types of transit-supportive roadway strategies are applied throughout the region. For example, Route 95 operates in curbside bus lanes in the suburbs, in mixed traffic along one of the region's parkways, in bus lanes downtown, on the freeway shoulder east of downtown, and in mixed traffic at the eastern end of the route. Queue jumps and TSP are applied as spot treatments throughout the city, and three TSP corridors have also been developed. The city's transportation plan identifies transit priority corridors, and many strategy implementations focus on these corridors. At the same time, OC Transpo uses input from bus drivers and others to identify locations that could benefit from projects and take advantage of road construction projects (e.g., water or sewer projects) to install transit-preferential projects or remove unwanted bus pullouts.

At the time of the interview with OC Transpo, TSP had been implemented at approximately 50 locations citywide and used bus-mounted transponders that were detected by in-pavement traffic signal detector loops. TSP is primarily provided as a green extension (i.e., keeping the traffic signal green longer than normal to allow a bus to pass through the intersection without delay) due to technological limitations of the city's signal controllers. In addition, because the system had difficulty distinguishing buses from other vehicles, the city was in the process of investigating alternative detection systems.

Other types of transit-preferential strategies that have been used in Ottawa are:

- **Phase reservice.** When two to three cars or a bus occupy a left-turn lane, the left turn may be served twice within the same signal cycle, both as a leading left turn and as a lagging left turn (i.e., both at the start and toward the end of when the intersection approach is served). This treatment was already used for non-transit applications (clearing queues of cars), so no special negotiating was needed with the city transportation department to use it, subject to the normal checks that there was sufficient capacity available to accommodate the extra left-turn interval. Staff have not observed any driver expectancy issues with the use of this treatment. It is only used during the morning peak period (6 a.m. to 9 a.m.).
- **Passive signal timing treatments.** OC Transpo staff evaluate intersection operations to identify whether shorter signal cycles or more green time for bus movements can be accommodated. In downtown, where 180 buses per hour operate in bus lanes on one-way streets, traffic signals are timed to allow buses to progress rather than automobile traffic.
- **Movement prohibition exemptions.** OC Transpo has installed bus-only left-turn lanes at key intersections where there is insufficient capacity to serve automobile left turns. At an intersection where right turns would be blocked by pedestrians, right turns are prohibited, but a bus route that turns right is allowed to make the turn. At a T-intersection with a two-lane approach (left-turn lane and right-turn lane), buses are allowed to make a left turn from the right-turn lane as a form of a queue bypass. A "Bus Excepted" tab on the lane-usage sign is used to indicate the allowed use.
- **Bus-only links.** Bus-only streets are used to link some neighborhoods that have limited street connectivity to allow bus routes to penetrate neighborhoods rather than go around them. These links are controlled only by signs, but OC Transpo believes that the violation rate is low.

OC Transpo's signal priority unit conducts any necessary data collection, analysis, reporting, and implementation associated with transit-supportive strategies. Public works staff have responsibility for reviewing and approving OC Transpo's requests and for making any necessary changes within the signal controller, but the staff have worked with each other for many years and are familiar with each other's capabilities. Both transportation and OC Transpo staff have access to signal controller cabinets; with the transportation staff working with the signal controller and OC Transpo working with the TSP equipment. Consultants are typically used for projects with a geometric design element.

Malmö, Sweden

Malmö, with a population of just over 300,000, is Sweden's third-largest city. The opening of the Öresund bridge–tunnel between Copenhagen and Malmö in 2000 created new public transport opportunities and a substantially increased commuter market from Sweden to Denmark. As of 2010, nonmotorized mode share in Malmö was approximately 57%. Public transport's mode share was 14%, a substantial increase from 8% in 2001, although most new transit trips appear to have switched from the walking mode (European Platform on Mobility Management 2013).

In 2003, Malmö initiated a program to improve cooperation with Skånetrafiken, the transit service provider (local bus, regional bus, commuter rail, and paratransit) for southern Sweden, with the goal of improving public transport service and usage. The impetus for this cooperation was the City Tunnel project (2005–2010), which created a direct rail connection between Malmö central station and the Öresund bridge with two new stations—one in an established urban district just south of the city center and another in a greenfield site close to the bridge. A major focus was restructuring the surface public transport lines to work with the new line and to serve the new stations. Agency partnerships were established at the political (i.e., city council/governing board), staff (i.e., agency leadership and planning and operations staff), and private-sector (e.g., contracted bus operator) levels. Working groups were formed in the following areas, with staff representatives provided as needed from the appropriate departments and organizations:

- **Service quality,** managing quality issues related to vehicles and drivers as well as safety and security issues;
- **Operations and maintenance,** addressing maintenance of streets and bus stops, snow removal, and construction-related route diversions and stop closures, among other issues;
- **Information and marketing,** addressing joint agency needs, particularly in the area of mobility management; and
- **Traffic and infrastructure planning,** looking at longer-term needs, such as long-term road or land use construction projects, permanent route and stop changes, and large-scale system expansion projects.

There is also a policy group that coordinates activities among the working groups and higher levels, a steering committee consisting of managers from Malmö's streets and planning departments and various departments within Skånetrafiken, and a presidium group with representatives of the agencies' governing bodies, the regional transport committee, and a technical committee.

One area of ongoing cooperation at the time of the Malmö interview was the Malmö Express BRT line. The line, which opened in June 2014, is operated with bi-articulated, 78-ft buses equipped with doors on both sides and is intended as a transitional service to provide more capacity and better service quality on Malmö's busiest bus route until a tram line along the same alignment is constructed around the end of the decade. At that time, the high-capacity buses will be moved to another line identified for future tram conversion. The line operates at 5-min peak headways along a 5½-mile route. The existing TSP system along the route has been upgraded. The alignment already had more than 2 directional miles of right-side bus lanes, and an additional 4 directional miles of median bus lanes were added in anticipation of the future tram line, with stations in the center of the street in those sections.

Malmö provides TSP at most signalized intersections throughout the city. The bus lane network consists of fairly short segments scattered around the city, and taxis are often allowed to use the bus lanes. Many bus lane sections have been installed as a means of complying with European Union air-quality requirements; if the nitrogen oxide levels from motor vehicles sitting in queues at intersections are too high, creating a bus lane is one means to address the problem. Other bus lanes have been installed as queue bypasses at congested intersections—one such lane on the main arterial approach to the city center from the northeast saves 3 to 4 min of delay per bus during the morning peak. Bus lanes are generally installed by taking a traffic lane, but city policy is to prioritize non-automobile modes; in many cases, the capacity is not needed between intersections. On occasion, short-term (15-min) parking is allowed in selected bus lane sections during off-peak periods when adjacent property access needs are important. Malmö has installed bus-friendly speed tables along transit corridors where general traffic speeds require calming; the design quickly elevates the roadway on the entry side similar to a speed table, but gently lowers the roadway back to grade on the departure side.

CHAPTER 3

Ingredients for a Successful Project

This chapter describes an effective practice for developing and implementing a transit-supportive roadway strategy (or package of strategies) by drawing on the experiences of transit and roadway agencies that have successfully worked together to implement projects. While developing a project may be easier in some jurisdictions than in others, this chapter provides a pathway for making improvements regardless of the local policy environment and provides case study examples derived from the TCRP Project A-39 interviews (see *TCRP Web-Only Document 66*) that demonstrate how others have been successful.

This chapter discusses the following topics:

- Developing agency partnerships,
- Working within the policy environment,
- Developing potential strategies,
- Working within the regulatory environment,
- Engaging project stakeholders,
- Implementing the project,
- Quantifying the results, and
- Building on success.

3.1 Developing Agency Partnerships

This step takes the longest to achieve and may not be fully reached until well after the first successful project has been implemented. Nevertheless, it is the most important step since almost all of the transit-supportive roadway strategies identified in this guidebook require the participation of one or more other agencies. Even when all of the participating parties are housed within the same governmental body (e.g., a city transit department, a city public works department, a city planning department), they often will have competing goals and objectives that will need to be reconciled.

Getting Started

The interviews conducted during the development of this guidebook identified many different ways that partnerships can start. These include:

- **Small steps.** The transit agency engages the roadway agency in focused areas, such as passing along information from bus operators about poorly timed traffic signals or when making improvements to bus stops related to the Americans with Disabilities Act (ADA). This approach opens lines of communication that produce small, positive results and produces staff relationships that can be built on in the future with larger projects.
- **Piggyback on other projects.** The transit agency tracks paving, widening, water, sewer, and utility projects on streets with bus service that are contained in a roadway or public works

agency's adopted capital improvement program that are located on streets with bus service. The transit agency works with the other agencies to identify transit-supportive roadway strategies that can be incorporated into the project, often at a lower cost than if they were performed as stand-alone projects. OC Transpo in Ottawa, Canada, works with the city department in charge of roadways to identify transit-supportive features that can be installed or undesired bus pullouts that can be removed whenever roadway projects are being planned. TransLink in Vancouver, Canada, worked with the provincial transportation ministry to incorporate bus-only ramps into a freeway widening project to support a freeway-based BRT route linking suburban communities to the region's rail system.

- **Regional engagement.** The transit agency is actively involved with local and regional planning efforts and existing interagency working groups and committees. The transit agency works to have transit priority corridors identified in local and regional long-range transportation plans, along with specific strategies or projects that could be considered or are desired in those corridors. Partner agencies become aware of the transit agency's desires and proactively consider transit-supportive features when planning their projects. For example, bus lanes in the Las Vegas, Nevada; Jacksonville, Florida; and Salt Lake City, Utah, regions came about as a result of state DOTs approaching local transit agencies about incorporating bus lanes into upcoming projects; these projects had previously been identified in local transportation plans. Having a project identified in local and regional plans is often a pre-condition for obtaining grant funding.
- **Political or agency leadership directives.** The election of a new mayor or the appointment of a roadway agency director can provide opportunities for transit agencies to create or sustain interagency relationships when the new leaders view transit as a necessary and beneficial service in their community. For example, although the New York City DOT and Metropolitan Transportation Authority (MTA)–New York City Transit (NYCT) had some experience working together, the Select Bus Service program really got going after both agencies got new leadership who were interested in aggressively pursuing BRT projects.
- **Major project involvement.** Major projects necessitate interagency partnerships, and these can sometimes leave a legacy of permanent organizational structures to facilitate interagency communication. Many agencies worked together to implement freeway-based BRT service in Los Angeles in conjunction with the development of tolled express lanes, and a formal project charter was developed describing each agency's role and responsibilities on the project. Malmö, Sweden, developed linkages at the political (city council/agency board), staff (agency leadership and planning and operations staff), and private-sector (consultants and contracted bus operators) levels originally to support the development of an underground rail link from Malmö Central Station to the Öresund bridge, leading to Copenhagen, Denmark. At the time of the interview with the group, it was working on its third joint activity, planning for transit improvements to implement by the year 2020.
- **Times of crisis.** Although it is not suggested that a transit agency wait until a crisis occurs to develop relationships with other agencies, crises can provide the impetus that forces agencies to work together to meet a near-term need, with the result that a long-term partnership is formed. For example, the shoulder bus lane network in Minneapolis began as a short-term response to flooding that closed a major freeway link and developed into a long-term "Team Transit" partnership involving multiple agencies and jurisdictions.

Building Momentum

Once lines of communication are open, taking some basic actions common to any successful project will help develop staff relationships and foster further agency interaction:

- **Build leadership support.** Obtaining the transit agency general manager's support for transit-supportive strategies in concept is an important first step because without this support, few staff or financial resources will be made available to pursue opportunities as they arise. The general manager can then work to build support among counterpart leaders at other agencies, who can help break down roadblocks that might be present at lower levels of their organizations.

- **Develop staff interaction.** Project staff from partnering agencies should have clear project roles and responsibilities. It is suggested that staff meet on a regular basis, even when no project is currently underway, as these meetings can also be used to identify potential locations for future projects. When transit staff and partner agency engineering and planning staff are comfortable working together and have strong relationships, projects are likely to go more smoothly. Staff familiarity will also help each agency keep its partner agencies' needs and interests in mind. King County Metro (Seattle, Washington) worked with its Seattle DOT staff partners to help it understand transit operations and to think of a bus route as a whole.
- **Understand each other's needs.** The needs and priorities of the partnering agencies may, at times, be at odds. Therefore, it is important for all involved parties to understand each other's needs so they can work toward mutually agreeable solutions. Most transit staff do not have an engineering background, and most transportation engineers do not have a transit background; therefore, staff may not be aware of the agency needs and policy environments that their counterparts operate under. Appendix A (for transit staff) and Appendix B (for engineers and planners) can help overcome these barriers by presenting basic transportation engineering and transit concepts related to transit-supportive roadway strategies. Of course, it is even better to talk directly with one's counterparts about their work and the constraints they operate under. Larger transit agencies may have enough projects to be able to support in-house traffic engineering staff positions.

Overcoming Resistance

Partner agencies may not immediately say yes to transit agency proposals for implementing particular transit-supportive strategies. This is often not a sign that these agencies are opposed to improvements that benefit transit, but rather that they need more information to support saying yes. Successful approaches that transit agencies have used to overcome resistance include:

- **Education.** In many cities, transit-supportive roadway strategies are not yet in the mainstream, many roadway agency design manuals do not discuss them, and until recently, coverage of these strategies in national documents has been limited. Therefore, the transit agency may need to educate its partner agencies about the benefits of these strategies and point them to sources of information, such as this guidebook and AASHTO's transit design guide (2014). The PowerPoint presentation developed under this project (available at the summary web page for this guidebook by searching for *TCRP Report 183* at www.trb.org) can be incorporated into such an effort.
- **Demonstrate the need.** Showing the problems the transit agency experiences in the field can help partner agency staff and other stakeholders understand the need for a solution. For example, the Central Ohio Transit Authority (COTA) took stakeholders on a bus tour of a route proposed for conversion to BRT to demonstrate the operational problems it faced on a daily basis.
- **Data and analysis.** Transportation engineers need data and analysis to support their decisions since they are professionally liable for the decisions they make. Many transit agency representatives interviewed as part of TCRP Project A-39 stated that the easiest way to work with roadway agency staff and to get a project approved was to prepare a traffic analysis for their proposal. The analysis demonstrated how the project would or would not affect various types of roadway users and could be used as a basis for supporting a project's approval. These analyses have been performed by in-house transit agency engineering staff, private consultants, and local universities. As roadway agencies gain experience with different strategies, local guidelines on their use can be developed.
- **Peer knowledge and experimentation.** Even with an analysis in hand, roadway agency staff may still have questions when something new, such as TSP, is being introduced to a jurisdiction.

King County Metro (Seattle, Washington) lent TSP equipment to smaller cities in the region so that staff could experiment with it in their signal shops, while the Seattle DOT conducted a weeklong test of TSP in the field to find out how it worked. Dallas Area Rapid Transit (DART) used FHWA's Peer-to-Peer program to send Dallas traffic signal engineers to two other cities to meet with their peers to learn how TSP had worked out in those cities.

- **Bring money or other benefits to the project.** Roadway agencies, just like transit agencies, face the challenge of greater needs than available resources, so when a transit agency can help fund a project, it can result in a roadway agency giving the project higher priority. COTA installed fiber-optic cable and made sidewalk and curb improvements that also benefitted the city. King County Metro set up intergovernmental agreements (IGAs) with local jurisdictions that committed the transit agency to making specified service improvements in exchange for the jurisdictions making specified infrastructure improvements.
- **High-level talks.** Meetings between agency leadership may help overcome staff opposition at lower levels of an organization.
- **Pick low-hanging fruit.** Transit agencies who operate regionally may find that some local jurisdictions are easier to work with than others. These agencies have found success with implementing projects in the short term with the communities who want to work with them, while working over the longer term to get more jurisdictions on board.

Case Study: New York City

New York City has implemented a form of on-street BRT that is branded Select Bus Service (SBS). SBS uses strategies such as dedicated bus lanes, off-board fare collections, and transit signal priority to provide faster, efficient, reliable transit service. At the time of writing, there were six SBS routes, with one more in development. Initial planning for the program goes back to the early 2000s, when NYCT became interested in transit-preferential treatments.

NYCT initially prepared a scope for a planning study to establish what BRT elements might work in New York City's context. NYCT sent the study to the city and state DOTs to see if they would be willing to participate in funding the study. The resulting corridor identification study involved both NYCT, which operates transit service within New York City, and New York City DOT, which has responsibility for any on-street changes that are required. The study provided an early opportunity for the two agencies to build a relationship.

The biggest impetus to the BRT program came in 2007, when both NYCT and New York City DOT got new leadership. Both agency heads were interested in an aggressive approach to BRT, which proved essential for getting the program off the ground. NYCT and New York City DOT have been able to maintain this leadership support with the success of the SBS program. The improved bus service has been well-received by the public, and all of the candidates for mayor in the last election prior to the interview said that they wanted more SBS corridors. The two agencies continue their collaboration as part of planning and implementation of the SBS routes.

In terms of formal agreements between the agencies, there is an overriding memorandum of understanding (MOU) that lays out the broad program concepts, such as that the city pays for street improvements and NYCT pays for bus service and fare collection equipment. There are also MOUs for small projects such as curb extensions, where the city has the money, but the transit agency's construction department can get the job done more quickly.

It was clear that BRT would only work if the program worked for both agencies. All of the planning and design needed to be coordinated. The agencies agreed on common objectives for the program: make buses run faster, improve ridership, and do not degrade traffic operations. In some cases, the program has actually improved traffic speeds and been able to maintain curb access where needed.

Case Study: Salt Lake City

The Utah Transit Authority (UTA) provides transit service in the Salt Lake City–Provo–Ogden region, including bus, light rail, commuter rail, and demand-responsive transit, with a streetcar line also under construction at the time of writing. The 35M MAX route in southern Salt Lake County was UTA's first BRT route and includes a 1-mile section with center-running bus lanes.

The 35M MAX project grew out of the region's long-range transportation plan, which identified the 3500 S roadway as a future light rail or BRT corridor. When the Utah DOT developed a widening project for 3500 S, it approached UTA to consider options for making the project multimodal. UTA determined through the Utah DOT planning process that BRT was the best fit for the corridor, given the existing land uses and available budget. Utah DOT worked with UTA to implement the center bus lanes, including taking agency staff to Vancouver, Canada, to see a median bus lane in operation, and contracting with the University of Utah to simulate bus lane and transit signal priority operation. The traffic analysis helped convince Utah DOT that the center lane would not significantly affect roadway operations and might even benefit automobile traffic. The region's experience with signal priority and center median stations for light rail also helped smooth the way for the implementation of BRT.

The region has a culture of working together (UTA, Utah DOT, the metropolitan planning organization, and local jurisdictions). In this case, Utah DOT approached UTA about making its project multimodal, and both the city and county worked to make coordination with UTA seamless during project development. Although Utah DOT and UTA have a positive relationship at high levels, the two agencies worked to keep this project corridor-focused, with decisions made locally and at lower levels in the organization. This approach reduced complexity and saved time by avoiding the need whenever possible to elevate decisions to higher levels in the respective organizations. UTA noted that having a good partnership with the DOT project manager was essential.

3.2 Working Within the Policy Environment

Understanding the roadway agency's policy environment—the criteria the agency uses when making decisions on transit-supportive roadway strategies—is important when identifying potential strategies to address a particular bus operations issue. Roadway agencies with a multimodal approach to serving road users will typically be more open to a wider range of potential strategies than agencies that prioritize motorized vehicle operations.

Examples of Policy Environments

The following scenarios are examples of the types of policy environments that might be encountered and how a transit agency might identify transit-supportive roadway strategies that can work within these environments, assuming that the transit agency's resources only allow funding lower-cost projects (i.e., no roadway widening).

Scenario 1: Maintain Existing Motorized Vehicle Operations

This scenario describes situations where the roadway agency requires that existing motorized vehicle operations be maintained and little flexibility is permitted. This might be the case where the roadway already operates below the roadway agency's operational standard and the roadway agency is seeking to avoid further degradation. In this case, the transit agency might wish to first consider transit operations strategies since these require the least amount of coordination with roadway agencies.

Scenario 2: Maintain or Improve Person Delay

In this scenario, the roadway again may not meet the roadway agency's operating standards, but the roadway agency is open to strategies that use the available right-of-way in the most efficient way. A common performance metric in this situation is the person delay, where the delay experienced by each mode (e.g., automobile delay, bus delay, pedestrian delay) is weighted by the number of persons using each mode. A strategy that results in a net reduction in person delay would be considered acceptable, even if automobile delay increases somewhat, as long as the intersection or roadway as a whole operates below capacity. (When intersections operate over capacity, the resulting queues can spill back to other intersections, creating new operational problems.) In this case, any of the traffic control and infrastructure strategies described in this guidebook that produce only small impacts to automobile delay will likely result in a net improvement in person delay. Any of the transit operations strategies would also be applicable.

Scenario 3: Maintain Operations at or Above Standard

Under this scenario, the roadway operates above the roadway agency's minimum standard (typically expressed in terms of level of service or volume-to-capacity ratio), and the roadway agency's policy does not require mitigation measures unless a project would degrade roadway operations below the minimum standard. This approach is similar to how land use developments or redevelopments are usually treated, in that the traffic from the developments is allowed to degrade roadway operations as long as the standard for minimum operations continues to be met. In this case, strategies that result in worsened automobile operations would be permitted to be implemented as long as the minimum operations standard is met. In locations where roadways have significant spare capacity, a wide range of possible strategies could be considered. The toolbox chapters of this guidebook note which strategies work better on congested roadways and which work better on less-congested roadways.

Scenario 4: Favor Transit Service

This scenario describes policy environments that favor transit service, even at the cost of vehicular operations. This might be a case where city policy expressly favors non-automobile modes, either in specified corridors or throughout the city (as is the case in some European cities). Strategies that provide improved transit operations would generally be viewed positively, subject to other potential formal or informal criteria such as:

- Safety performance (e.g., roadway safety should not be degraded),
- Roadway capacity (e.g., below-capacity operations should be maintained),
- Access and parking considerations for adjacent land uses,
- Minimum level of transit usage (e.g., minimum hourly bus frequency), and
- Cost/benefit considerations.

In a policy environment that favors transit service, transit-supportive roadway strategies are easier to implement because support likely already exists from leadership, agency partners, and other stakeholders. (Otherwise the policy would not have come into being.) As noted in *TCRP Report 165: Transit Capacity and Quality of Service Manual* (Kittelson & Associates et al. 2013), "investments in bus preferential treatments rather than expanded roadway capacity may be seen as a means of further improving transit attractiveness and maximizing roadways' person-carrying ability."

Identify Low-Hanging Fruit

When working within policy environments that are less supportive of transit improvements, incremental improvements may be more successful (Kittelson & Associates et al. 2013). A good approach may be to combine a bus operations strategy, such as stop relocation, that has relatively low costs and relatively few stakeholders, with a roadway-focused strategy that has low costs and few constraints. Transit operations strategies can often provide the largest portion of the overall travel time benefit when implemented in conjunction with other strategies, while an easy-to-implement traffic control or infrastructure strategy can result in a positive outcome for the roadway agency. The combination of the two can open the door to demonstration projects for other strategies or agency collaboration on more-challenging projects.

Plan in Advance and Take Advantage of Opportunities

Regardless of the policy environment, it is important to plan for the future implementation of transit-supportive roadway strategies. Potential approaches are as follows:

- Work to incorporate transit projects or transit priority corridors into long-range transportation plans. This approach starts the conversation early on with partner agencies and can help change the existing policy environment.
- Identify projects in other agencies' plans and capital improvement programs (e.g., roadway paving, widening, access management, water or sewer work) that could lend themselves to incorporating transit-supportive features. This approach helps transit agencies capitalize on cost savings and efficiencies associated with improvements being made as part of a larger project, while roadway agencies benefit from having another funding source to help defray the project's design costs.
- Identify potential funding sources or grants to help jump-start projects. This approach may get roadway agencies to prioritize a project since they are not being asked to take on the full cost of the project.

Case Study: Jacksonville, Florida

Jacksonville Transit Authority (JTA) provides transit service within the city of Jacksonville. In Florida, major urban streets are typically state highways under the jurisdiction of the Florida DOT. Thus, implementing transit-supportive roadway strategies in Florida often requires local transit agencies and Florida DOT to work together.

Blanding Boulevard (State Highway 21) is an arterial street that feeds traffic from southwestern Jacksonville into the city center. It had been identified since 2002 as a future rapid transit corridor. While JTA had discussed bus rapid transit and bus lanes with Florida DOT, it did not have any construction dollars to use. However, when Florida DOT was planning a resurfacing project for Blanding Boulevard, it saw an opportunity to restripe the existing, little-used parking lane as a bus lane and began working with JTA to do so. In this case, the roadway's traffic operations were improved (by removing the parking) and the roadway space was used more efficiently, so the project fit within the existing policy environment and provided benefits to both agencies.

JTA developed typical bus lane sections and led preliminary design and public involvement efforts (with consultant help). Florida DOT's Jacksonville urban office incorporated the preliminary design into its resurfacing plans (also using consultants), handled design variances (none turned out to be needed) and signs, and advocated for the project at the Florida DOT district level. The project was completed in 2009.

Case Study: Eugene, Oregon

Lane Transit District (LTD) in Eugene, Oregon, has implemented two BRT lines since planning first began in 2000, when BRT was a relatively new concept nationally, and much of the first line ran along a state highway. LTD's first challenge was to educate the city and the Oregon DOT about the BRT concept generally and the operation of transit signal priority specifically. The city traffic engineer had an established relationship with the Oregon DOT regional engineer and could explain in technical terms how the TSP system would work. This interaction was helpful in getting the Oregon DOT engineer on board with the project, but further work was needed educating staff from other levels of Oregon DOT as they became involved in the project. Once those staff understood the project, things progressed relatively smoothly.

A policy challenge that needed to be overcome was that the city's planning department did not want the route on a straight line between two stations because that alignment would have required eliminating on-street parking, which was a hot topic politically at the time. The transit agency compromised by placing one direction of BRT on the street, which turned out to produce better bus operations.

Case Study: Vancouver, Canada

TransLink has operated on-street BRT routes (B-Lines) since the late 1990s. At the time of the interview with the agency, a new B-Line was being planned for King George Boulevard in the city of Surrey, in the southern part of the Vancouver region. Once the primary route from Vancouver to the United States border, the former King George Highway is being transformed into an urban boulevard, and transit-supportive roadway strategies are being planned in conjunction with this project. Surrey is a rapidly growing part of the region and is one of the larger municipalities in the region. Although the municipality is not a transit service provider itself, there is strong support in Surrey to help improve transit service. The city's capital plan, for example, includes transit-supportive roadway strategies. Although Surrey participates in project cost-sharing and is designing the overall project, TransLink provides most of the funding.

The new B-Line is being implemented in two phases. The initial phase, which opened in 2013, is an L-shaped route connecting two transit centers to central Surrey and rail transit. One pair of queue bypasses already existed along the route and two more were added. At some point in the future, when the route is extended south to White Rock, just north of the United States border, more queue bypasses will be constructed at congested intersections. A consultant study identified potential locations for particular strategies. Transit signal priority is a possibility, but no specific plans have been made.

One of the corridor's advantages is that a lot of right-of-way is available due to the boulevard's former status as a highway, and the city is investigating how best to use the right-of-way. Improvements under consideration include narrowing lanes to urban street widths (11.5 to 12 ft); adding bicycle lanes, cycle tracks, or two-way bike paths; removing right-turn channelization islands at intersections; and adding curbside parking in places to help create an urban feel. Each of these non-transit features will need to be considered when evaluating individual strategies. In addition, signal timing in the corridor will be adjusted to better move peak-direction traffic.

3.3 Problem Identification and Strategy Development

Understand the Problem

Before doing anything else, the transit agency should ask itself what the problem is that needs to be solved and determine whether transit-supportive roadway strategies are the best approach to solving that problem. The strategies presented in this guidebook are best suited to addressing bus speed and reliability problems, but not every cause of a speed or reliability problem can be addressed by these strategies. Examples of causes of unreliability that are not well-suited to being addressed by transit-supportive strategies are long-term road construction, buses breaking down while in service, inadequate bus and operator availability, insufficient time allocated in the schedule, differences in operator driving skills and route familiarity, and environmental conditions (e.g., rain, snow). Causes of slow speeds or poor reliability that can be addressed by these strategies include traffic congestion, traffic signal delays, street network patterns, increased passenger demand, and the number and location of bus stops.

Bus operators and field supervisors can be valuable sources of information for identifying locations where transit-supportive roadway strategies can help improve bus operations. Transit agencies that have automatic vehicle location (AVL) and automatic passenger counter (APC) equipment on their buses (and have a formal program to archive and access that data) can use this information to identify where and when speed and reliability problems occur, quantify the magnitude of the problem, and quantify how many passengers are affected by the problem. *TCRP Report 113: Using Archived AVL-APC Data to Improve Transit Performance and Management* (Furth et al. 2006) provides guidance on using AVL and APC data in this way.

If at all possible, try to quantify the magnitude of the problem, both to help with prioritizing projects and to eventually quantify the outcome of the strategy or strategies that end up being implemented. Quantifying the benefits of a strategy helps make a stronger case for the next implementation, may help in securing funding for future projects, and if shared with the transit community (e.g., through papers and presentations), can benefit others seeking to implement these strategies. If the implemented strategy was not as successful as anticipated, the reasons for this can be evaluated and used to inform future decision making.

Match Potential Strategies to the Problem

Once the problem has been clearly identified, it becomes possible to identify potential solutions. Chapter 4 provides guidance on the situations that particular strategies are best suited for and can be used as a starting point for identifying strategies to consider further.

Analyze Potential Benefits and Costs

The detailed strategy descriptions provided in Chapters 5 through 8 can be used to narrow in on a preferred strategy or set of strategies. These descriptions provide the relative costs of different strategies, benefits and disbenefits to buses and other roadway users that have been observed in previous implementations, situations in which an otherwise appropriate strategy may need to be removed from consideration, and implementation guidance.

Once a preferred strategy or set of strategies has been identified, it is advisable to conduct a more detailed analysis to forecast the anticipated benefits, given the local conditions in which the strategy would be implemented, and to estimate the cost of implementing the strategy, given knowledge of current local costs. This analysis will be useful in the next step in persuading the roadway agency to approve the project and can also be used to support funding requests. The analysis may also indicate that the preferred set of strategies may not produce a good benefit relative to the cost, in which case the transit agency will need to change the strategies being considered.

Case Study: San Francisco, California

In 2006, the San Francisco Municipal Transportation Agency (SFMTA) and the city Controller's Office conducted a detailed evaluation of the city's transit system (Muni) to identify ways to improve service, attract ridership, and improve efficiency. During the initial planning phase of the Transit Effectiveness Project (TEP), from October 2006 to November 2007, SFMTA collected and analyzed an extensive amount of data, including customer market research on passenger preferences and priorities for transit service, travel pattern data, and route-by-route ridership data.

Based on this research, best practices from other cities, and stakeholder input, SFMTA developed a set of preliminary recommendations. In 2008, SFMTA conducted public outreach (including more than 100 community meetings along with discussions with decision makers) on the preliminary recommendations and presented a refined set of recommendations to the SFMTA board. The board endorsed the draft recommendations for environmental review in October 2008.

At the time of the interview with the agency, the project was toward the end of a 2-year environmental review process under the California Environmental Quality Act that analyzed the entire TEP as one project. A consequence of this approach was that none of the proposed service changes or bus priority projects could be implemented before the review was completed. In anticipation of a successful review, SFMTA coordinated a funding plan including the San Francisco County Transportation Authority (SFCTA) and the metropolitan planning organization (the Metropolitan Transportation Commission [MTC]). Service improvements were being coordinated through SFMTA's operating budget discussions. Bus priority capital projects were being planned for funding through multiple sources, including SFCTA, MTC, discretionary federal money, and coordinating with other city departments (e.g., Public Works, to get curb extensions constructed when repaving occurs).

3.4 Working Within the Regulatory Environment

Transportation engineers typically work with three basic types of policy direction: standards, guidance, and state or local practices, depending on the agency or jurisdiction. Standards generally have no room for variation or interpretation by the engineer unless a specific process is provided for granting deviations. Guidance is essentially a recommendation for best practice, with room for interpretation on its applicability to specific locations. Practice is how roadway agencies apply higher-level (i.e., national or state) guidance to roadways under their jurisdiction. State standards and guidance typically exist for use on state facilities but may also apply to local facilities when funds originate with the state or are passed through the state.

Transit-supportive roadway strategies are still an emerging area of traffic engineering practice and are not fully accounted for in current standards, guidance, or practices. Therefore, particularly the first time a particular strategy is used in a community, there is often a need to identify constraints and either work within them or look for opportunities to modify them.

Identify Potential Regulatory Constraints

State and local roadway design manuals and standards describe how roadways should be designed and are intended to result in safe, well-functioning roadways. These standards often incorporate all or portions of the national standards and guidelines described in Appendix A, such as the *Manual on Uniform Traffic Control Devices.* Failing to adhere to these standards can arguably give rise to an inference that the proper standard of care of a professional engineer was not used, which can lead to serious legal implications for agencies and their engineers. Therefore, it is important to identify early on whether a transit-supportive roadway strategy under consideration may conflict with existing standards.

Occasionally, local laws and regulations may also affect a transit agency's ability to implement a desired strategy. For example, Lane Transit District wished to place a busway in the median of a street in Eugene, Oregon, as part of a BRT route under development. However, existing trees in the median were more than 50 years old, and the city's tree ordinance specifies that a public vote is required to cut any tree more than 50 years old. As a result, the busway design needed to be modified to create a two-directional, single-lane facility that avoided impacts to the trees. The California Highway Patrol raised objections to planned bus shoulder use on a San Diego–area freeway because state traffic laws did not permit shoulder driving, even by authorized vehicles. The detailed strategy descriptions in Chapters 5 through 8 indicate which strategies may require reviewing or changing laws prior to implementation.

Identify Potential Design Standard Variances

Existing standards may not always allow for the most efficient implementation of a desired strategy. However, in many cases, roadway agencies have set up a formal process to approve a variation from a standard when doing so would not compromise safety and there are clear benefits to implementing a strategy. This approach provides greater flexibility to adapt roadway projects to their local contexts and is becoming more mainstream among roadway agencies. This approach is essential to continuing innovation because every roadway element was used for the first time at some point and had to undergo a similar process of experimentation and evaluation. However, to reduce potential liability, it is important to clearly document the reasons for the variance.

The FHWA describes a formal process for applying for permission to experiment with new traffic control devices and for performing those experiments if approved. This information is provided in Section 1A.10 of the MUTCD (FHWA 2009) and is summarized in Appendix D of this guidebook.

Case Study: Minneapolis, Minnesota

Team Transit is a program that the Minnesota DOT established in the late 1980s to identify ways to make better use of transit on freeways and to alleviate congestion without spending the resources needed to widen freeways. As part of this initiative, ramp-meter bypasses for buses were constructed at a number of locations. One such project would have required rebuilding a section of the freeway to meet side clearance standards. Instead, the decision was made to build the ramp meter and accept that it could not meet existing standards; no negative impacts were observed as a result. In order to create advantages for buses and implement innovative strategies, variances from long-existing roadway standards needed to be made. In the longer term, Minnesota DOT used the experience gained from the design variances to develop more bus-friendly standards that were still acceptable to FHWA.

Minnesota DOT staff stated in the interview that a pragmatic approach is best for these kinds of projects: get most of what an agency wants accomplished for less money than trying to fix everything for a lot of money. Re-examine existing design standards since transit improvements will probably violate some of them. Above all, have the organizational structure in place that supports innovation, or the project will not happen.

Case Study: New York City

As part of the development of its Select Bus Service BRT routes, New York City has developed bus lanes on a number of streets. To make the lanes as self-enforcing as possible, the city DOT and the transit agency desired to color the bus lanes red, a relatively common strategy used internationally. However, because the MUTCD specifies how colored pavement markings can be used as traffic control devices and because red pavement was not specified as an allowed use, New York needed to request permission from FHWA to experiment with red bus lanes, which FHWA granted.

New York completed the required evaluation report on the effect of red paint on lane violations and other operational and safety issues, which the FHWA accepted. As a result, New York is allowed to continue to use this treatment. Other cities, such as San Francisco, have subsequently started their own experiments. It is anticipated that this treatment will be included in the next edition of the MUTCD, but until such time, agencies will continue to need to request to experiment. A template for such a request is provided in Appendix D.

3.5 Engaging Project Stakeholders

No matter the size of the project, there will likely be a need for the transit agency to engage stakeholders other than the roadway agency. For a bus stop relocation, this may simply involve the adjacent property owner(s). For a large corridor project (e.g., a BRT route incorporating bus lanes and other strategies), an extensive stakeholder engagement effort will likely be needed.

Potential Stakeholders

Persons, groups, and organizations that might need to be involved in the project include, depending on the type of strategy and scale of the project:

- Public agencies
  - Transit agency capital projects, service planning, and marketing staff; bus operators; agency management and board; and representatives of other transit agencies that might use a facility
  - Roadway agency roadway design, traffic signals, and traffic operations staff; pedestrian and bicycle coordinators; and agency management (for each jurisdiction affected by the project)
  - City and county decision makers (e.g., city manager, city council members, mayor) (for each jurisdiction affected by the project)
  - Local and regional planning agency staff
  - Law enforcement, fire department, and other emergency responders
  - Staff from other potentially affected agencies (e.g., parks district, utility district, economic development department, school district)
- Community organizations
  - Neighborhood associations, community boards
  - Business associations, chamber of commerce
  - Churches
  - Advocacy groups for bicyclists, pedestrians, and persons with disabilities
- Institutions
  - Schools, universities
  - Hospitals
- Individuals, businesses, and nonprofits
  - Business owners
  - Property owners
  - Delivery companies, taxi companies, armored car companies, and others needing curb space
  - Social service agencies

Techniques for Engaging Stakeholders

Some of the techniques described in Section 3.1 to develop agency partnerships also apply to engaging stakeholders:

- **Demonstrate the need.** An important point to communicate is the purpose of the proposed strategy (or strategies) and how it will benefit the transit agency and its passengers.

- **Listen to and understand stakeholder needs.** By gaining an understanding of stakeholder concerns and challenges, better, mutually beneficial results can be achieved. Meet with anyone who would like to discuss project issues. These meetings provide an opportunity to clarify the project, correct any misconceived notions, and build support.
- **Education.** Representatives from several interviewed agencies noted that it is very important to have a team member on board who is good at explaining the engineering side of the work in terms that all stakeholders can comprehend. Demonstrating that the proposed concept has worked successfully in other locations also helps.

Other techniques focused on non–public agency stakeholders are:

- **Accommodate stakeholder schedules.** The business community in Columbus, Ohio, preferred having meetings early in the morning rather than in the evening. The transit agency had much better meeting participation when they were scheduled according to stakeholder preferences. Lane Transit District (Eugene, Oregon) started visiting small businesses along a proposed BRT corridor since the business owners did not have time to attend the meetings. It allocated three staff members to walk the corridor and talk with each business owner on the route, which developed good relationships.
- **Personal touch.** Another technique that worked well in Columbus was having the main project lead personally invite stakeholders to meetings. The invitation could be a personal email, letter, or call, but the response from this personal level of detail was much greater than that from generic letters or emails.
- **Find ways to accommodate concerns.** For example, a project in Jacksonville, Florida, converted a parking lane to a bus lane. Although the parking lane was not well-used, those who did use it, including a school that used it for student drop-offs on weekdays, were initially opposed to losing it. The transit agency used its contractor to develop a new circulation plan for the school (off the arterial) that the school ultimately preferred.

Regardless of the size of the project, keep stakeholders informed by communicating early, clearly, and often. Large projects will require a correspondingly large number of meetings; several interviewees who had implemented corridor projects held more than 100 meetings over the course of their projects. These can include one-on-one meetings with individual stakeholders, technical steering committee meetings, advisory committee meetings, workshops, open houses, and meetings of decision-making bodies.

Finally, following up with stakeholders after a project is implemented, and making corrections if necessary, can help maintain good stakeholder relations for future projects. TriMet has found it beneficial to follow up with stakeholders after the opening of a project to check on punch-list items, make sure things are going as expected, and check that maintenance agreements are being followed.

Case Study: New York City

NYCT has many different stakeholders involved in its projects. These include MTA (a state-level organization), NYCT staff, New York City DOT staff, New York State DOT staff, the metropolitan planning organization (MPO), and some of the city's 57 community boards. In addition, large hospitals, businesses, and schools along a Select Bus Service project route are included as stakeholders. Finally, any other businesses or groups that may be affected by a potential bus stop location are included. Stakeholder meetings inform people about what is going on and obtain their input on the street's needs. The agencies have found that a workshop setting has been more effective than a presentation/question-and-answer format. The workshop setting, with smaller groups, helps get better community feedback, helps the community explain its needs in a clearer way, and generally functions better than a large group. NYCT staff recognize the need for being flexible and handling each stakeholder's needs and requests with an approach that fits the stakeholder's personality best. While some stakeholders respond best to a direct, no-holds-barred approach, others respond best to a more laid-back or soothing approach.

At the onset of every project, a community advisory committee is convened. The advisory committee is typically involved in six meetings throughout the duration of the project planning process. One meeting discusses stop locations, one discusses neighborhood parking needs, one focuses on business delivery needs, and the other three cover project-specific issues that need to be addressed. All affected parties would attend each meeting and all be in the same room. The room would then have breakout sessions according to where on the corridor a particular attendee was located. In all, NYCT has held over 400 meetings for all of their Select Bus Service routes that were either operational or in some stage of planning at the time the interviews were conducted.

Case Study: Spokane, Washington

STA worked with stakeholders, including internal staff from multiple departments, several local jurisdictions, and the general public on a bus stop consolidation project. The stakeholders started their involvement in the project at varying places in its development. The STA Planning Department was involved during the initial phase. The STA Service Improvement Committee was shown initial drafts of the project and assisted in refining the project scope. The STA Facilities and Grounds Department was involved after the draft plan was developed and advised on the project scope since they were responsible for removing the bus stop signs. Fixed-route bus operators were involved during the draft phase when they were provided information and maps for review and comment. The general public was involved during the draft phase when information was provided via web reports, online surveys, and signs posted at bus stops that were planned to be closed. Local jurisdictions became involved during the final draft phase when they were provided information on locations and timelines for removals.

Various levels of meetings were held during the project for information dissemination and project planning. The Planning Department held meetings to discuss the project and gather input. The Service Improvement Committee held regular biweekly meetings during project development, and bus stop consolidation projects were added to the agenda for these meetings regularly during the initial planning phase as well as later when discussion items warranted it. The Facilities and Grounds Department met to discuss the scope and schedule estimates to provide input on what its staff could accomplish for physical removal of bus stop signs. Fixed-route operators were provided with draft location maps to review and comment on. STA staff were available to meet with operators to discuss the project and address concerns. No public meetings were held.

3.6 Implementing the Project

At this point, the project has been approved and funded and is ready to be implemented. Depending on the type and scale of the project, either the transit agency or the roadway agency might lead the project using in-house staff, consultants, or a combination of the two.

Intergovernmental Agreements

It is a good idea to establish MOUs or IGAs that specify the role of each partner agency in planning, funding, designing, constructing, operating, and/or maintaining the project. *TCRP*

Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic (Danaher 2010) provides the following examples of agreements related to transit-supportive roadway strategies:

- An IGA between a transit agency and a city for constructing improvements in a corridor;
- An IGA between a transit agency and a city to improve transit speed and reliability in the city;
- An IGA between a transit agency and a service provider to improve transit speed and reliability;
- A local agency agreement between a transit agency, a city, and a state DOT to implement transit signal priority on a state-owned arterial within the city; and
- An interlocal agreement between a transit agency and a county to operate and maintain transit signal priority.

TCRP Legal Research Digest 42: Transit Agency Intergovernmental Agreements: Common Issues and Solutions (Thomas 2012) provides additional examples of agreements applicable to transit-supportive roadway strategies:

- An IGA between a city, county, and others to fund capital improvements, maintenance, and operation of transit service;
- An agreement between a transit agency and a county to install utilities along a roadway as part of a BRT project;
- An interagency agreement between a transit agency and a city to make use of the city's expertise when conducting preliminary engineering for a BRT project;
- A master cooperative agreement between a transit agency and a city to develop a street corridor BRT project;
- A common use agreement between a transit agency and a DOT to allow the perpetual use of, maintenance of, and future modifications to DOT facilities to allow the construction, maintenance, and use of transit facilities;
- An IGA between a transit agency and a county to allow the installation of bus stop improvements;
- An MOU between an MPO and a transit agency describing the manner in which the MPO will provide staff assistance;
- An MOU between an MPO and a transit agency describing the respective agencies' functions and responsibilities;
- A master agreement between an MPO and a DOT "outlining terms and conditions of collaboration to deliver transportation improvements that utilize the materials, funds, resources, or services of both parties"; and
- A license issued by a city to a transit agency to use city right-of-way in connection with transit service expansion.

Constructing the Project

The activities involved in constructing a transit-supportive roadway project are generally similar to that of any other construction project and are not covered here in detail. The Additional Resources sections of the detailed strategy descriptions in Chapters 5 through 8 list documents that may be consulted when implementing specific strategies (e.g., transit signal priority).

Additional Outreach

Additional outreach to the public or partner agencies may be required when larger projects get ready to open. If a project is introducing new traffic regulations (e.g., bus lanes), the public needs to be educated about how they are (or are not) to be used. Similarly, law enforcement agencies need to be ready to enforce any new regulations and should be aware (where necessary) of any transit exemptions from traffic regulations—something that is best addressed early during stakeholder engagement but definitely should be addressed at this point if it has not been before. New fare payment methods and new stop locations will require educating transit passengers, and a number of transit agencies have deployed customer service staff (supported by distributing marketing and information materials prior to opening) along the corridor during the first days of operation.

Transit agency representatives interviewed for this project also emphasized the need to plan for a smooth start-up. For example, it was suggested to let all city departments know about the project to decrease the chances of any construction occurring on opening day (or any other day) that would decrease the new system's effectiveness. Another transit agency in a city with a normally mild climate experienced a snowstorm soon after a project opened and realized then that no maintenance agreement was in place with the city to handle snow removal from the transit lanes.

Project Schedule

A theme that came up in the interviews many times with the transit agencies that had implemented large-scale projects was not to underestimate the time required to take a project from the planning stage to opening day. Establish adequate milestones with expected outcomes, and build contingencies into the schedule to address challenges that arise during the course of the project. Some of the things that led to schedule delays were:

- Difficulty obtaining a key stakeholder's buy-in to the project;
- Time required to vet different design options with stakeholders and achieve consensus;
- Insufficient coordination between city staff on potentially competing issues (e.g., bicycle needs, freight needs), which then surfaced later in the project; and
- Re-evaluating bus stops proposed to be closed, based on customer feedback once notices were placed at the stops.

Case Study: Portland, Oregon

This case study looks at issues that came up during the course of adding light rail tracks to the existing downtown bus mall in Portland, Oregon. One issue related to traffic control was the need to develop special lane-usage signs to inform motorists on the mall and turning onto the mall from side streets which lane to use. In addition, special permission was required for the signal faces; a green up arrow was desired to reinforce the "No Turns" message at certain intersections, which would normally require a 12-in. signal face, but the other signal faces would only be 8 in., which would have looked odd.

TriMet would have liked to use raised domes as a barrier to separate the automobile and transit lanes, but the city thought it would be unsafe if bicycles hit the domes. As a compromise, high-profile thermoplastic striping (two 8-in. white stripes) was used in conjunction with overhead signs at intersections, but maintenance has been an issue since buses cross over the striping in places to make left turns off the mall, which wears it away. In retrospect, using concrete for the transit lanes could have helped differentiate the two types of lanes.

Other issues that had to be addressed during construction and implementation were:

- Moving bus operations to two other streets during mall reconstruction, including moving shelters and installing curb extensions;
- Addressing adjacent property access needs, including prisoner drop-off at a courthouse, fire station egress, and hotel loading zones;
- Maintaining the special architectural elements used along the mall; and
- Educating passengers about where buses would stop following reconstruction.

Transit mall maintenance costs are divided among the city, TriMet, and Portland Mall Management, a nonprofit corporation funded by the city, TriMet, the Portland Business Alliance, and Portland State University. The city maintains the automobile pavement markings, signs, lighting, and traffic signal system. Through a contract, TriMet maintains the striping delineating the vehicle and transit lanes. TriMet also maintains the light rail infrastructure. Portland Mall Management is responsible for trash pickup and maintaining shelters.

Case Study: Jacksonville, Florida

An implementation challenge that JTA faced with its new bus lane was how to sign the lane since it was the first of its kind in Florida and signs had not been identified as an issue at earlier stages of the project. Right turns would be allowed from the bus lane at driveways and intersections. JTA wanted signs that would work well for its drivers and overall bus operations, while Florida DOT wanted to make sure the lane would operate safely. Florida DOT's Traffic Operations section developed the signs. The sheriff's office was unfamiliar with bus lanes and said it would not enforce the lanes, but fortunately, bus drivers have not reported any significant compliance issues. In addition to JTA buses, school buses and county transit vehicles can use the lanes.

Before the bus lane was restriped, a public awareness campaign was conducted on how to use it. The campaign started in July 2008, prior to a February 2009 opening. Flyers were mailed to every household within a mile of the corridor (November), while a video presentation was shown at schools and malls (through December), and on the JTA website (still available at the time of writing). Billboard messages were installed along the corridor and left in place until a month after opening. Finally, variable message signs were installed on major cross streets warning motorists to watch out for buses; these were in place for a couple of weeks following project opening.

3.7 Quantifying the Results

Once a significant project has been implemented, the transit agency may need to monitor it and collect data to quantify its results. This is useful for ensuring successful project results and to support future project decision making. Due to staff time and funding limitations, this is a step that transit agencies have often omitted, with the result that they lose out on its potential benefits. (However, large-scale projects that receive funding from the Federal Transit Administration's New Starts program are now required to perform before-and-after studies.) Another challenge is separating out the individual effects of particular strategies implemented as a package, although projects implemented over a series of several phases can overcome this challenge.

Data Applications

Monitoring the project results is important for assessing how the project affected transit and other modes. This is useful for:

- Identifying and correcting any unexpected negative project impacts,
- Judging what factors contributed most to the project's outcomes,
- Assessing the accuracy of any preliminary analysis done to forecast operations with the project (i.e., microsimulation), and
- Quantifying operational benefits of the project that can justify future projects.

Potential Performance Metrics

There are a number of potential evaluation measures that can be used to quantify the results that consider transit and other affected modes. Some possible metrics are:

- **Travel delay for transit and other vehicles.** Compare the change in delay (i.e., at an intersection) before and after the project for transit and automobiles (and potentially pedestrians and bicyclists, if they are significant users of the intersection).
- **Travel time/speed for transit and other vehicles.** Compare typical speeds in the project area for transit and automobiles before and after the project. Bluetooth readers, global positioning system (GPS) data, or traditional speed tests can be used for the comparison.
- **Reliability.** Compare changes to travel time variability for automobiles and transit, or evaluate changes in bus on-time performance.
- **Vehicle emissions.** Estimate changes in vehicle emissions as a result of the project, perhaps using models that relate to vehicle volumes and speeds.
- **Operation costs.** Compare operating costs for the affected route(s) before and after the project, including changes in cost trends.
- **Ridership.** Compare ridership before and after the project.
- **Safety.** Compare crash history before and after the project. (This requires several years of "after" data for a fair comparison.)

3.8 Building on Success

Once the project is complete, it is important to consider other opportunities to build on the project's success. For instance, continuing to monitor the project and assess results can help identify further fine-tuning or improvements. As more data are collected over time and agencies become more comfortable with the project's outcomes, it may be feasible to refine the strategy or implement new strategies. Some roadway agencies may initially be hesitant to pursue transit-supportive roadway strategies due to concerns about automobile operations, but they often become more open to implementing more strategies when they have a positive first experience with a strategy.

The resulting opportunities from a successful project may extend beyond transit-supportive roadway strategies to include things such as:

- Expanded agency partnerships between transit and roadway agencies,
- Support for more multimodal projects and a complete-network mindset that recognizes the importance of providing for all users and modes, and
- Greater comfort with testing new innovative treatments.

CHAPTER 4

Selecting an Appropriate Strategy

4.1 Overview

This guidebook identifies 34 different strategies that can directly improve bus speeds or reliability or that can help support other strategies in reaching their full effect. As there are many possible causes for speed and reliability problems, and most strategies focus on a particular issue, it is important to understand the cause of the problem (see Section 3.3) prior to starting to identify potential solutions. In addition, understanding the local policy (Section 3.2) and regulatory (Section 3.4) environments will help to narrow down the list of candidate strategies to ones that can be implemented in the local context. This chapter provides guidance on (1) potential criteria to use for selecting strategies and (2) matching strategies to causes of bus speed and reliability issues.

4.2 Potential Selection Criteria

Traditional Approach

Many reference documents have recommended specific bus volume "warrants" for constructing transit-specific roadway strategies, in particular bus lanes. All of these warrants can be traced back to the same source, *NCHRP Report 155: Bus Use of Highways—Planning and Design Guidelines* (Levinson et al. 1975). Although *NCHRP Report 155* was careful to note that environmental and policy considerations, as well as the ability of other streets to accommodate diverted traffic, could result in lower warrant volumes, this guidance has not always been carried through to later documents. The stated philosophy underlying the *NCHRP Report 155* warrants is that the number of people using a bus lane should at least equal the number of people served by a general traffic lane; however, at least in some cases, these minimum bus volumes result in considerably higher person volumes in the bus lane relative to a typical urban street general traffic lane.

One problem with using the *NCHRP Report 155* bus volume warrants is that they assume a particular policy environment; namely, one where jurisdictions provide transit priority only when transit use is already so high that a de facto bus lane is created by the presence of the number of buses needed to serve those passengers. However, jurisdictions may have other priorities (e.g., minimizing person delay, increasing non-automobile mode share, reducing automobile emissions) that are not considered by this approach or are even worked against by this approach. Jurisdictions may also wish to prioritize different modes on different streets, and a one-size-fits-all approach to selecting transit-supportive strategies does not fit well with this desire.

A second problem with applying warrants is that traffic engineers understand a warrant to be a minimum, but not necessarily sufficient, criterion for justifying a traffic control or roadway design feature. If the warrant is not met, the feature would not be provided. Thus, applying rigid warrants can often work against a jurisdiction's desire to improve transit service because the warrants may suggest that bus volumes are insufficient to justify the strategy, even though other factors may well suggest that the strategy will provide a net benefit to the community.

Transportation engineering practice has been evolving in recent years toward a more flexible approach to evaluating potential roadway design strategies, as evidenced by the Context Sensitive Solutions (FHWA 2014) and Complete Streets (Active Transportation Alliance 2012) movements. A review of transit-supportive roadway strategies implemented by 52 transit agencies in the United States and Canada (Danaher 2010) found that nearly all considered multiple factors when evaluating strategies and did not apply the *NCHRP Report 155* warrants. The most recent guidance documents, such as AASHTO's transit design guide (2014), also suggest considering a range of factors when evaluating potential strategies. This guidebook follows that approach.

Comprehensive Approach

The decision to implement a transit-supportive roadway strategy needs to take into consideration and balance the needs and desires of the transit agency and its passengers, other roadway users, and the community as a whole. Consequently, multiple decision-making criteria are suggested.

From the transit agency perspective, AASHTO (2014) identifies the following principles as potential reasons for justifying transit-supportive strategies:

- Provide priority to road users using less-polluting, more space- and energy-efficient, and less-costly (to society) travel modes;
- Allocate roadway delay proportionally among all roadway users;
- Protect the public investment in transit service; and
- Give an advantage to vehicles that maximize person throughput.

As the transit agency is frequently responsible for the cost of implementing transit-supportive strategies, the cost of implementing the strategy relative to its benefits is an important consideration. The less expensive the strategy, the more passengers it benefits, and the less the strategy affects other road users, the more likely it will be to show a net benefit.

From the roadway agency perspective, the roadway operations and design standards applied to the project will set the frame for what may or may not be possible to implement, considering transit and general traffic delay, road user safety, and pedestrian and bicycle accommodations, among other factors.

The community perspective will consider such factors as:

- Improvements to the community's mobility options,
- Support for the community's long-term economic development vision,
- Support for community goals to promote greater use of non-automobile modes, and
- Environmental impacts (AASHTO 2014, Kittelson & Associates et al. 2013).

The types of criteria that transit agencies reported using to evaluate their transit-supportive roadway strategies reflect a balance of these different perspectives. In decreasing order of use, these were:

- Potential bus travel time savings/speed improvement,
- Potential bus reliability improvement,
- Ridership (route and stop levels) and number of buses,
- Traffic volumes and level of service,
- Safety,
- Benefit/cost ratio,

- Street widths, and
- Street functional class and adjacent land use environment (Danaher 2010).

4.3 Problems and Potential Strategies

There are many possible causes for bus speed and reliability issues; these can either be external to the transit agency or under its control. Likewise, there are often several possible strategies that can address these issues. This section lists some common sources of speed and reliability issues and provides guidance on strategies to consider to address them. As will be seen, a problem can often be addressed from several different angles—through operational changes on the part of the transit agency, through changes in traffic control, and through physical changes to the roadway.

Detailed descriptions of each strategy, including potential constraints on the use of the strategy and other important factors to consider before selecting one, are provided in the toolbox chapters (Chapters 5 through 8).

Increasing Ridership

Increased ridership is a good problem to have but can also lead to longer dwell times that reduce bus travel times. Increasing the route frequency is one option that helps reduce the number of passengers boarding and alighting at a given stop and the number of standees in the aisle, both of which reduce dwell time, but operating funds may not be available to support an increase in frequency. Other options include changing the way fares are paid, such as encouraging greater use of prepaid fare media or allowing all-door boarding in conjunction with proof of payment (Section 5.4) or using larger buses on the route (Section 5.5) to reduce congestion in the aisle.

Route Design

Two elements of route design can affect bus speeds. The first is the number of times that buses have to stop to serve bus stops. The second is the number of turns made along the route.

Consolidating closely spaced stops (Section 5.2) can be a relatively low-cost method to improve bus speeds without significantly inconveniencing passengers. A survey (Boyle 2013) found that this action was most frequently cited by transit agencies as the "most successful action taken" to improve bus speeds.

Some turns may have been introduced into a route long ago, but the justification for diverting or turning the route at that location may no longer exist. A comprehensive review of route design (Section 5.3) may identify opportunities to streamline a route to reduce delays caused by unnecessary turns or by turning at a location that experiences high delays. A survey (Boyle 2013) found that this strategy was tied for second (with transit signal priority) in being cited by transit agencies as the "most successful action taken" to improve bus speeds.

Some route diversions may also be necessary because the existing street network does not provide through connections for motor vehicles between locations that would preferably be connected by transit service or require a roundabout routing to serve. In these cases, bus-only links (Section 7.7) that provide such connection for buses while preventing undesired cut-through traffic may be an option.

Frequently, though, turns are a necessary evil on a route. In this situation, strategies are available for minimizing the delay experienced by buses when making a turn or when weaving across traffic lanes to access a left-turn lane. At traffic signals, options include any strategy discussed later to reduce traffic signal delay, plus bus-only signal phases (Section 6.9) and pre-signals

(Section 6.11). At any type of intersection, allowing buses to make turns that are prohibited to other vehicles for traffic operations or neighborhood traffic management reasons (Section 6.1) can result in a faster, more direct routing. In a transit-supportive policy environment, other potential options at unsignalized intersections may be traffic signal shadowing (Section 6.6) and traffic signals installed specifically for buses (Section 6.12).

Delays Leaving Stops

On higher-volume streets and at intersections where traffic signals and stop signs create queues of vehicles, buses may experience significant delays finding a gap in traffic to leave the bus stop and proceed along their route. If the bus stop is located in a bus pullout, eliminating, relocating, or consolidating this stop with a nearby bus stop (Sections 5.1 and 5.2) may be an option. If a parking lane is provided along the street, extending the curb into the parking lane at the bus stop (Section 7.5) allows buses to stop in the travel lane and proceed when ready. At traffic signals with right-turn lanes or available width from a parking lane, a queue jump (Section 6.10) can allow buses to re-enter the travel lane ahead of other traffic. Bus lanes (Section 8.1) are a potential option for BRT routes, streets with unused capacity (e.g., one-way streets), and streets with higher volumes of buses. Finally, implementing yield-to-bus laws (Section 6.3) is a potential option.

Traffic Signal Delays

Traffic signals are both a significant source of bus delay and a significant contributor to bus travel time variability. Fortunately, a number of potential strategies are available to minimize these delays. One challenge in implementing signal-related strategies is that, while these strategies tend to provide greater bus benefits as traffic volumes approach the intersection's capacity, intersection operations near capacity also tend to constrain a roadway agency's ability to adjust the signal timing or phasing without severely affecting the overall intersection operation. Consequently, these strategies often have the most potential when volumes are relatively high (so a significant bus delay reduction can be achieved) but not when intersections are at or close to capacity (so some flexibility is available to make changes to the signal control). A second potential challenge to be aware of is that traffic signal controllers may need to be upgraded to implement some of the strategies.

A low-cost starting point is to identify traffic signals where the existing timing does not appear to work well for buses or general traffic (e.g., where the signal is red but no side-street vehicles or pedestrians are being served) and could benefit from retiming. Some transit agencies have established formal processes for receiving tips from bus operators about poorly timed signals and passing them along to the appropriate roadway agency to be investigated (Boyle 2013). A more involved approach applying the same principles is to evaluate signal timing in general along a street (Section 6.4), identify potential opportunities to increase green time for the intersection approaches served by buses, reduce the traffic signal cycle length, or improve the progression provided between pairs of signals. These actions can benefit all traffic using the intersection, not just buses. Relocating bus stops from the near side to the far side at intersections (Section 5.1) is an effective, low-cost way to avoid delays caused by right-turning traffic. Phase reservice (Section 6.5) can also be a low-cost option for reducing delays to buses making left turns at an intersection or operating on low-volume side-street approaches.

Other available options will require investments in new traffic signal infrastructure and, potentially, infrastructure onboard the bus. TSP (Section 6.7) offers the potential to significantly reduce traffic signal delays and improve travel time reliability and was frequently cited in a survey as being the "most successful action taken" by a transit agency to improve bus speeds (Boyle 2013). However, there have also been a number of documented instances where little or no travel time benefit was obtained—either because the schedule was not adjusted to take advantage of potential time savings or because the time saved at one intersection was lost at the next intersection (e.g., because although the bus arrived earlier at the next intersection, it was not able to pass through the intersection any sooner). Therefore, it is important to evaluate the potential benefits of TSP implementation as a corridor, rather than intersection by intersection, prior to committing to a significant capital investment.

Other signal-related strategies that might be considered in some circumstances are bus-only signal phases (Section 6.9), queue jumps (Section 6.10), and pre-signals (Section 6.11).

Congested Roadways

Roadways that operate over capacity—whether because traffic demands exceed a traffic signal's capacity to serve them or because of physical bottlenecks that reduce the roadway's capacity—are a particular challenge to address. Over-capacity operation manifests itself as long and growing queues of vehicles. It can take several traffic signal cycles for vehicles to get through the signal, or many minutes to get past the point where a roadway narrows. Strategies to address these situations work by managing the queues or providing ways for buses to move around the queues. These include bus shoulder use (Section 7.3), queue bypass lanes (Section 8.6), pre-signals (Section 6.11), and contraflow bus lanes (Section 8.8).

Other Traffic-Related Delays

Strategies to address traffic delays not associated with traffic signals or exiting bus stops include the following:

- Turn restrictions (Section 6.2), where vehicles stopped to make turns (particularly left turns when no left-turn lane is available) delay both buses and general traffic;
- Speed hump modifications or removals (Section 7.1) to eliminate bus delays caused when buses must slow well below the posted speed to safely traverse the hump; and
- Bus lanes (Section 8.1), which remove some to nearly all of the traffic interference (depending on the bus lane type) experienced by buses traveling in mixed traffic.

In addition, standard traffic engineering techniques outside the scope of this guidebook, such as providing turn lanes, can improve traffic flow for both buses and general traffic.

Support Strategies

Some strategies do not provide a direct travel time or reliability benefit on their own but help make another strategy possible or help another strategies achieve its maximum effectiveness. These include:

- Enforcement (Section 6.13), which supports bus lanes and bus-only links by discouraging their use by unauthorized vehicles;
- Red-colored pavement (Section 7.4), which supports strategies such as bus lanes, bus-only links, and turn lanes restricted to buses by improving their conspicuity and thereby reducing their use by unauthorized vehicles;
- Bus stop lengthening (Section 7.2), which may be required when longer buses are introduced on a route or routes are consolidated on a street on which bus lanes have been implemented;
- Boarding islands (Section 7.6), which make bus stops possible along left-side bus lanes, some types of reversible bus lanes, and queue jumps accessed from channelized right-turn lanes; and
- Transit signal faces (Section 6.8), which provide special vertical and horizontal bar go and stop indications to buses to avoid potential driver confusion if regular red/green/yellow indications were used.

Packages of Strategies

Many strategies lend themselves to being implemented in conjunction with other strategies, thereby increasing the overall benefit to transit vehicles. The Companion Strategies sections in the toolbox chapters (Chapters 5 through 8) describe which other strategies work well with a given strategy.

4.4 Evaluating Strategies on a Corridor Basis

Most literature on transit-supportive roadway strategies—including this guidebook—presents bus delay benefits from intersection and other spot treatments on a per-site basis. However, it is important to be aware that the time saved at one location may be lost at the next downstream traffic signal under some circumstances, resulting in no net benefit.

This situation could occur, for instance, when transit signal priority gives a green signal 10 s early to the bus's approach, allowing the bus to depart 10 s sooner than it would have otherwise. An evaluation of the effect of signal priority at this intersection would say that it saved the bus 10 s. However, assume that the bus arrives at a near-side stop at the next traffic signal 10 s early, but by the time it is finished serving passengers, the signal has already turned red and the bus has to wait until the next green to continue. In this situation, the bus departs the second intersection at exactly the same time it would have if no signal priority had been provided at the first intersection—the delay saved at the first intersection is converted into additional signal delay at the second intersection, and the bus ends up with no net benefit from the strategy in this case.

Therefore, when estimating the benefit of a transit-supportive strategy at a given location, it is important to consider whether the next downstream signal will negate the effect of the strategy. The likelihood that this will happen depends on the relative timing of the two signals (i.e., when the second signal turns green relative to the first), the time required for a bus to travel between the two signals, bus dwell time (and dwell time variability) accumulated between the signals, and the amount of green time provided. Appendix C of the TCRP Project A-39 final report (*TCRP Web-Only Document 66*), building on work by St. Jacques and Levinson (1997), describes an analytical method for estimating the likelihood that a bus will be able to make the green light at a downstream signal and thus preserve the delay benefit provided by a strategy implemented upstream.

4.5 Strategy Selection Matrix

Table 5 presents a summary of key benefits, costs, and issues associated with each of the transit-supportive strategies described in this guidebook. It also presents a brief description of one or two common applications for each strategy. The table can be used as a quick reference for identifying potential strategies applicable to a particular situation. The reader can then turn to the corresponding strategy description in the strategy toolbox (Chapters 5 through 8) for detailed information and guidance. Bold type in the table indicates typical uses or outcomes out of the wider range given in the table.

Table 5 provides the following information:

- **Typical application.** One or two typical situations when the strategy might be applied. The Applications sections in the strategy toolbox provide more comprehensive listings of applications.
- **Traffic volumes.** Typical traffic conditions under which the strategy is most applicable: low = volume-to-capacity (v/c) ratios < 0.5, moderate = v/c ratios of 0.5 to 0.8, high = v/c ratios

Table 5. Strategy selection matrix.

Strategy and Section Number	Typical Application	Traffic Volumes	Bus Volumes	Bus Speed	Bus Reliability	Auto Speed	Planning Costs	Capital Costs	Other Issues
BUS OPERATIONS STRATEGIES									
Relocate stop (5.1)	Near-side stop	L to **H**	Any	+ to ++	+	+	L	**L** to M	1,2
Consolidate stops (5.2)	Short stop spacing	Any	Any	++ to +++	0 to +	0 to +	M to H	L	2,3
Route design (5.3)	Route deviations	Any	Any	++++	0 to +	0	**M** to H	L	2,4
Fare payment (5.4)	Long dwell times	Any	Any	+ to +++	0 to +	0 to +	M to **H**	M to **H**	4,5
Vehicle changes (5.5)	Long dwell times	Any	Any	+ to ++	0 to +	0 to +	L	H	3,6,7
TRAFFIC CONTROL STRATEGIES									
Movement restriction exemption (6.1)	Turns in route	**L/M** to H	Any	+++ to ++++	0 to +	- to 0	M	L to M	8
Turn restrictions (6.2)	Delays from turning cars	Any	Any	+ to +++	+	- to +	M	L	8,9
Yield to bus (6.3)	Offline bus stops	Any	Any	0 to ++	0 to +	-	M to H	L to H	10
Passive signal timing adjustments (6.4)	Signals	L to M	Any	0 to ++	0 to +	- to **+**	M	None	11
Phase reservice (6.5)	Bus turns at signal	L to M	Any	++ to +++	+	- to +	L to M	0 to M	9,12
Traffic signal shadowing (6.6)	Bus turning delay at unsignalized int.	**M** to H	L	++ to +++	0 to +	-	M	M	13
Signal priority (6.7)	Signals	M to **H**	L to M	0 to ++	++	- to +	M to **H**	H	9,10,12
Transit signal faces (6.8)	Signals	Any	Any	0	0	0	L to M	M	10,14
Bus-only phase (6.9)	Unusual bus move	L to H	Any	++ to +++	0 to +	-	L to M	**0** to M	10,12,14
Queue jumps (6.10)	Signals	M to **H**	L to M	+ to ++	0 to +	-	L to M	M to H	10,12,15
Pre-signals (6.11)	Bus lane end	M to VH	M to H	+ to +++	+	- to 0	M	M to H	1,11,14
Bus traffic signal (6.12)	Turn at unsignalized int.	M to H	M to H	+++	+	-	M-H	H	8,11,16
Enforcement (6.13)	Fares, traffic control	Any	Any	0 to +++	0 to +	0	H	0	14,17
Enforcement (photo/video) (6.13)	Bus lanes, bus-only links	Any	Any	0 to +++	0 to +	0	H	H	10,14,17
INFRASTRUCTURE STRATEGIES									
Modify speed hump (7.1)	Speed humps	Any	Any	+ to ++	0	0 to +	M	L to M	5,7,8
Lengthen bus stop (7.2)	Short bus stops	Any	M to VH	0 to ++++	+	0 to +	L	L to M	1,3
Bus shoulder use (7.3)	Suburban arterials	VH	L to H	++++	++	0	H	M to H	5,8,9,10,20
Red pavement (7.4)	Bus lanes	Any	Any	0	0	0	M to H	M to H	14,16
Curb extensions (7.5)	Low-speed urban streets with peds	L to M	**L** to M	+ to ++	+	**- to +**	L to M	M	2,18,19
Boarding islands (7.6)	Non-curb bus stops	Any	Any	0	0	0	L to M	L to H	2,14
Bus-only links (7.7)	Subdivisions, urban centers	0	**L** to H	++++	0 to +	0	L to M	L to M	5
BUS LANE STRATEGIES									
Bus lanes, generally (8.1)	BRT, high bus volumes	M to H	L/M to **H**	++ to +++	+	- to 0	H	L to **H**	5,9
Curbside (8.2)	Preserve travel lanes	Same	L/M to **H/VH**	0 to +++	0 to +	Same	Same	Same	1
Shared bus/bike (8.3)	ROW constraints	Same	L to M	Same	0 to +	Same	Same	Same	1,21
Interior (8.4)	Preserve parking	Same	Same	Same	Same	Same	Same	Same	
Left-side (8.5)	Right-side traffic congestion	Same	Same	Same	Same	Same	Same	Same	2
Queue bypass (8.6)	Bottleneck	H to VH	Same	++++	Same	0	Same	Same	21
Median (8.7)	Minimize traffic interference	Same	Same	Same	Same	Same	Same	Same	2
Contraflow (8.8)	Strong directional flow	H to VH	Same	++++	Same	Same	Same	Same	2,8
Reversible (8.9)	ROW constraints	M to VH	Same	Same	Same	Same	Same	Same	2,8,21

Notes: 0 = none, L = low, M = moderate, H = high, VH = very high. Int. = intersection, “Same” = same as for bus lanes generally. Bold type indicates typical situations. See Table 6 for the “Other Issues” notes.

Table 6. "Other Issues" notes for the Table 5 strategy selection matrix.

(1) curb space usage by others	(12) signal controller capability
(2) passenger access to stops, ADA considerations	(13) alternative strategies more desirable if feasible
(3) bus stop/bus lane capacity	(14) support strategy that allows other strategies to work better
(4) spot treatment or system-wide application	(15) bus ability to access bus lane
(5) enforcement	(16) FHWA experimentation request needed
(6) maintenance facility upgrades, staff training	(17) may add to transit agency operating costs
(7) passenger quality of service	(18) motor vehicle ability to pass stopped buses
(8) safety	(19) bus dwell time
(9) part-time or conditional operation feasible	(20) shoulder width and pavement strength
(10) changes to traffic laws or design standards	(21) ROW availability
(11) traffic signal coordination	

of 0.8 to 1.0, and very high = *v*/*c* ratios > 1.0, considering the potential magnitude of bus delay savings and the strategy's flexibility to accommodate high-volume situations.

- **Bus volumes.** Typical bus volumes under which the strategy is most applicable: low = <10 buses per hour per direction, moderate = 10 to 30 buses per hour, high = 31 to 100 buses per hour, and very high = >100 buses per hour. Under favorable policy environments, lower bus volumes than indicated may be appropriate.
- **Bus speed.** Typical bus delay benefit, on a per-site or per-block basis: 0 = no effect, + = <5 s, ++ = 5 to 15 s, +++ = 16 to 60 s, and ++++ = >60 s. The Benefits sections in the strategy toolbox provide quantitative data.
- **Bus reliability.** Relative impact on bus travel time variability: 0 = no effect, + = positive impact, and ++ = larger positive impact relative to other strategies. The Benefits sections in the strategy toolbox provide additional qualitative and quantitative information.
- **Automobile speeds.** Relative impact on automobile travel times: - = worsens automobile travel times, 0 = no effect, and + = improves automobile travel times. The Benefits and Cost Considerations sections in the strategy toolbox provide additional information, depending on whether the impact is positive or negative.
- **Planning costs.** Effort required for planning, analysis, and stakeholder coordination, relative to other strategies: low, moderate, high. The Cost Considerations sections in the strategy toolbox provide additional information.
- **Capital costs.** Typical capital costs on a per-site or per-block basis: 0 = none, low = <$10,000, moderate = $10,000 to $100,000, high = >$100,000. The Cost Considerations sections in the toolbox provide additional information, as well as information on strategy impacts on maintenance and bus operations costs not shown in the table.
- **Other issues.** Other important issues to consider when evaluating the strategy. This list is not comprehensive; see the Constraints and Implementation Guidance sections in the strategy toolbox for potential additional issues that may need considering in some circumstances, along with Appendix C on managing bus and bicycle interactions at bus stops. The numbers in the "Other Issues" column in Table 5 are explained in Table 6.

CHAPTER 5

Bus Operations Strategy Toolbox

This chapter is the first of four toolbox chapters presenting potential strategies for improving bus speeds and reliability. The strategies presented in this chapter are ones that transit agencies can implement on their own, with relatively little coordination needed with roadway agencies beyond that normally required for siting bus stops. These strategies are frequently implemented as part of a package of changes along a route or street—particularly when starting BRT service. Chapter 6 presents traffic control strategies that can be considered in combination with bus operations strategies, Chapter 7 presents infrastructure strategies (other than bus lanes), and Chapter 8 presents bus lane strategies.

The following strategies are discussed in this chapter:

- Relocating stops at intersections (e.g., from the near side to the far side of intersections),
- Optimizing bus stop spacing,
- Revisiting route designs,
- Introducing fare payment changes, and
- Introducing new bus vehicle types or equipment.

Each strategy is presented in its own section. These are organized as follows:

- **Description.** What the strategy does.
- **Purpose.** Why the strategy might be considered.
- **Applications.** How the strategy can be applied.
- **Companion strategies.** Other strategies that can be implemented in combination with the strategy.
- **Constraints.** Factors that may make the strategy infeasible or more challenging to implement in certain circumstances.
- **Benefits.** How the strategy can benefit bus operations and, potentially, other stakeholders.
- **Cost considerations.** Relative impacts of the strategy on transit agency and other stakeholder costs, including planning and coordination needs, capital costs, maintenance costs, bus operations costs, and other roadway user and stakeholder costs.
- **Implementation examples.** Examples of transit agencies that have implemented the strategy and, where available, short summaries of their experiences with it.
- **Implementation guidance.** Guidance on how and when to implement the strategy.
- **Additional resources.** Other documents that provide more information about the strategy or certain aspects of the strategy.

5.1 Stop Relocation

Description

An existing bus stop is moved from its current location at an intersection (e.g., near side) to a different location (e.g., far side).

Purpose

Buses serving near-side bus stops at signalized intersections frequently fall out of any traffic signal progression provided to traffic along the street. That is, the traffic signal is green when the bus arrives, but by the time the bus is finished serving passengers, the signal may have turned red and the bus must then wait for the next green signal before it can proceed.

Whether or not traffic signal progression is provided, buses at near-side stops at signalized intersections may be delayed entering or exiting the stop because they can be blocked by queued vehicles ahead of them. Right-turning vehicles, in particular, cause delays because they have to wait for any conflicting bicyclists and pedestrians to clear. The effect of queued vehicles is most pronounced when stops are located at or near the near-side stop bar (Cesme et al. 2015). Situations where some buses are able to proceed before the signal turns red, while others cannot, can lead to bus reliability issues, because some buses experience traffic signal delays while others do not. This delay variability is a particular issue if the waiting time until the next green signal is long.

Applications

Near-side to far-side relocations can be considered at any near-side bus stop at a traffic signal. Relocations from other locations to near-side locations are typically performed in conjunction with other strategies, either (1) to take advantage of an opportunity to implement a near-side strategy, or (2) because other considerations (e.g., location of passenger generators, transfer opportunities) dictate a near-side bus stop location. To avoid the need for buses to stop twice, San Francisco's Muni uses near-side stops at intersections where the bus would stop anyway for a stop sign (Boyle 2013).

Companion Strategies

Stop relocations are often implemented as part of a package of improvements for an intersection, route, or street, including stop consolidation (Section 5.2), route design changes (Section 5.3), transit signal priority (Section 6.7), bus-only signal phases (Section 6.9), queue jumps (Section 6.10), curb extensions (Section 7.5), and bus lanes (Section 8.1).

Constraints

The general considerations that apply whenever a new bus stop is placed also apply to stop relocations. These include:

- Potential for driveways, alleys, or other access points to be blocked;
- Potential for traffic to stop behind the bus and back up into the intersection (primarily a concern for streets with one travel lane in the direction of travel, in combination with online bus stops);
- Parking and delivery needs for adjacent land uses;
- Locations of passenger generators and transfer opportunities at the intersection (e.g., walking distances, number of street crossings required);
- Physical obstructions (e.g., trees, fire hydrants, lamp posts);
- Ability to meet ADA accessibility requirements;

- Ability to provide passenger amenities (e.g., shelters, electrical connections for bus arrival displays);
- Presence of bicycle facilities (see Appendix C); and
- Use of curb extensions (see Section 7.5) (Kittelson & Associates et al. 2013).

Benefits

As with any strategy involving spot locations, the sum of the delay benefit for a route or along a street will generally be less than the sum of the individual bus stop delay benefits since the delay saved at one stop is sometimes lost at a downstream traffic signal. See Section 4.4 for more information.

Delay Benefits: Far-Side Stops

Simulation testing conducted during TCRP Project A-39 at an isolated signalized intersection found that a far-side stop location:

- Produced an average 2.4 s less delay for buses than a near-side location when the intersection's *v*/*c* ratio was 0.5, 3.5 s at a *v*/*c* ratio of 0.8, and 8.8 s at a *v*/*c* ratio of 1.0;
- Resulted in slightly lower vehicle delays on the intersection approaches used by buses (0.6 s down to 0.1 s for the same range of *v*/*c* ratios); and
- Resulted in slightly lower average intersection delay for all vehicles (0.6 to 2.7 s for the same range of *v*/*c* ratios).

The intersection had a 160-s traffic signal cycle length, and buses received a green signal for 49% to 56% of the overall cycle length, depending on which direction they approached the intersection from. Bus dwell times averaged 20 s, with a standard deviation of 15 s.

Other studies in the literature have found similar results. Modeling by Furth and SanClemente (2006) found that the extra delay associated with near-side bus stops located at or near the stop bar, relative to a far-side stop, increased with increasing *v*/*c* ratio and as the traffic signal cycle length increased from 60 s to 90 or 120 s. When the green time provided to a bus was 50% of the cycle length (i.e., a green-time [*g*/*C*] ratio of 0.5), the extra delay associated with a near-side stop ranged from 1 to 4 s for a *v*/*c* ratio of 0.6, to 5 to 9 s for a *v*/*c* ratio of 0.8, depending on the cycle length. A study of a bus route on an arterial street in Portland, Oregon, using automatic vehicle location data found a travel time reduction of 24 s per mile in segments with far-side bus stops, equating to an average of more than 4 s per intersection (Feng et al. 2015). Simulation modeling by Cesme et al. (2015) found an average reduction in delay of approximately 7 s for far-side stops, relative to near-side stops, at a *g*/*C* ratio of 0.5, with the delay reduction increasing as the *g*/*C* ratio decreased.

Reliability Benefits: Far-Side Stops

Combined results from Furth and SanClemente (2006) and Cesme et al. (2015) show that the delay associated with far-side stops is generally insensitive to traffic signal cycle length, intersection *v*/*c* ratio, the amount of green time provided to buses, and the ratio of dwell time to cycle length. Near-side delay, on the other hand, is sensitive to all of these factors when the bus stop is located at or near the intersection. This means that a bus's overall delay at a signalized intersection will be generally the same for each bus with a far-side stop but will vary by time of day (as traffic volumes and signal timing patterns change) and by bus (as passenger demand and thus dwell time varies by bus) with a near-side stop. As a result, travel times will be less variable (i.e., more reliable) when far-side stops are used at signalized intersections than when near-side stops located at or near the intersection are used.

Delay Benefits: Near-Side Stops

In some instances, near-side stops can result in delays that are similar to or less than those of far-side stops (Furth and SanClemente 2006, Feng et al. 2015, Cesme et al. 2015). These include:

- Near-side stops in bus lanes where right turns are prohibited (less delay);
- Short traffic signal cycle lengths (e.g., 60 s) (similar delay);
- Long dwell times relative to the traffic signal cycle length (e.g., dwell times that are 75% or more of the cycle length) (similar to less delay); and
- Near-side stops set back from the intersection far enough to be outside the influence of queues (similar delay).

Cost Considerations

- **Planning and coordination costs.** Relatively low, but will vary depending on whether an individual stop is being affected, or a larger-scale (route or street) project is being developed. Stop relocations should be coordinated with the appropriate roadway agency. It is also desirable to engage adjacent property owners in advance about potential negative impacts to them of a stop relocation (e.g., loss of parking, waiting passengers congregating in front of buildings).
- **Capital costs.** Relatively low on a per-stop basis, consisting of removing infrastructure (e.g., bus stop poles, shelter) from the old site, installing infrastructure at the new site, and making any required ADA improvements, such as a landing pad. The need for concrete paving at the bus stop to reduce bus-caused pavement damage may also be considered.
- **Maintenance costs.** Will most likely be unchanged, unless the transit agency decides to upgrade the stop's amenities as part of the overall project.
- **Bus operations costs.** Reduces bus travel time and travel time variability.
- **Other user costs.** Slightly reduced delay for motorized vehicles on the intersection approach and for the intersection as a whole. No change in pedestrian and bicycle delay.

Implementation Examples

Examples of cities that have implemented large-scale stop relocations are:

- Portland, Oregon;
- San Francisco, California; and
- Victoria, British Columbia (Koonce et al. 2006, Boyle 2013).

In addition, 18 of 59 transit agencies responding to a survey for *TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds* had relocated stops to improve bus speeds.

Implementation Guidance

Exhibit 6-9 in the TCQSM (Kittelson & Associates et al. 2013) lists the advantages and disadvantages of different bus stop locations from a variety of perspectives. From a bus operations perspective, far-side stops at signalized intersections generally produce better bus travel time reliability than near-side stops located at the intersection stop bar. They typically produce less delay than near-side stops in the following circumstances:

- Moderate to long traffic signal cycle lengths (e.g., 90 s or longer);
- Relatively short dwell time relative to the traffic signal cycle length (e.g., less than 75% of the cycle length); and
- No bus lane provided or right turns allowed from the bus lane.

Near-side stops located at the intersection stop bar typically produce less delay than far-side stops with:

- Short traffic signal cycle lengths (e.g., 60 s);
- Bus lanes that prohibit other motorized vehicles, especially those making turns;
- Intersections with one-way streets where right turns are prohibited; or
- Bus stops located at a stop sign.

Near-side stops set back from the intersection beyond the 95th-percentile queue length operate similarly to far-side stops in terms of delay and reliability. They may be more inconvenient for passengers than far-side stops because passengers who have to walk through or past the intersection when traveling to and from their ultimate destinations will have to walk farther. However, these locations often work better than a near-side stop-bar location when a bicycle facility is located along the right side of the street (see Appendix C).

Near-side stops that are set back from the intersection within the area where vehicles queue are generally the worst locations from a delay and reliability standpoint since it becomes more likely that a bus will have to stop multiple times (e.g., behind the queue, at the stop, and at the traffic signal). The closer the stop is to the intersection (without actually being at the stop bar), the larger the negative impact. In addition, this location encourages right-turning traffic to cut in front of buses, leading to potential conflicts with both buses and bicycles.

Additional Resources

- ADA Standards for Transportation Facilities (U.S. Access Board 2006)—design guidance.
- *TCRP Report 19: Guidelines for the Location and Design of Bus Stops* (Texas Transportation Institute 1996)—design guidance.
- *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition (Kittelson & Associates et al. 2013)—Chapter 6 provides an analytical method for estimating a bus stop location's impact on bus speeds; Exhibit 6-9 presents advantages and disadvantages of different bus stop locations.
- *TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds* (Boyle 2013)—implementation examples.
- *TCRP Synthesis 117: Better On-Street Bus Stops* (Boyle 2015)—examples of current practice to address challenging bus stop locations and working with public agency partners to develop bus stops that meet transit agency and passenger needs.

5.2 Stop Consolidation

Description

Bus stop spacing is optimized—typically by increasing the spacing—so that buses make fewer stops along the route while minimally affecting the area served by transit.

Purpose

Every time a bus stops to serve passengers it can experience delay above the time required to serve those passengers. Typical types of delay that can be experienced with each stop include:

- **Acceleration and deceleration delay.** Extra time used slowing to a stop and subsequently accelerating back up to speed compared to going past the stop at speed. A typical value is 10 s of delay when traveling at 25 mph; the delay is higher as the bus speed between stops increases.

- **Door opening and closing time.** Stopped time before and after passengers board and alight. Typical values are 2 to 5 s.
- **Traffic signal delay.** After serving passengers, the bus may need to wait for the traffic light to turn green again, when it could have made it through the signal if there was not a bus stop. Typical delays can range from 0 to 70 s, depending on when the bus is ready to depart the stop and the traffic signal cycle length.
- **Reentry delay.** If the bus has to wait for other traffic to clear before it can pull out of the stop and back into the traffic, it experiences reentry delay. Typical values range from 0 to 10 s at stops not at a traffic signal to 0 s up to the length of the green interval at a traffic signal (Kittelson & Associates et al. 2013).

When buses tend to stop at the same set of stops along the route each trip, the headways between buses will be more consistent and the reliability will be better.

Applications

Stop consolidations are typically implemented either (1) as a route-specific or system-wide effort to improve bus travel times, or (2) in conjunction with introducing new types of bus service such as limited-stop or BRT routes.

Companion Strategies

Stop consolidations are often implemented in conjunction with stop relocations (Section 5.1).

Constraints

When a bus stop is closed, passengers will need to be able to safely walk to the next-closest stop, which means that a sidewalk connection needs to be available, and, if applicable, safe crossing opportunities need to exist at any intersections along the way. This issue is particularly important for elderly passengers and those with disabilities; if they cannot access another stop, they will need to switch to paratransit service, which is typically considerably more expensive for the transit operator to provide (Kittelson & Associates et al. 2013).

The experience of several transit agencies that have implemented system-wide stop consolidations is that passengers will object to having their stop removed if it means they have to walk farther to the next stop, and that this is the biggest obstacle to overcome when implementing a stop consolidation program. Twelve of 59 agencies responding to a survey said that they had considered, but not implemented, stop consolidations due to ADA reasons (e.g., no accessible route to the next stop) or customer convenience considerations (Boyle 2013).

Care is required when consolidating stops adjacent to the stops with the highest passenger volumes along a street or route because shifting additional passengers to the busiest stops may reduce the stop's capacity to serve buses. When the number of buses scheduled to use the stop is at least half the stop's capacity, the potential for "bus stop failure" is increased; this is where a bus has to wait to enter the stop because buses ahead of it are still using the stop (Kittelson & Associates et al. 2013).

Benefits

Bus Delay Benefits

The experience of some transit agencies that have measured the impact of stop consolidations is summarized in the following:

- TriMet experienced a 5.7% reduction in travel time as a result of a 6% to 8% increase in average stop spacing. No change in ridership was observed (El-Geneidy et al. 2006).
- Muni experienced 4.4% to 14.6% increases in speeds as a result of reducing the average stop spacing from 5.9 to 2.5 stops per mile (Diaz and Hinebaugh 2009).

- LACMTA (Los Angeles County Metropolitan Transportation Authority) found that bus running times for its first two BRT routes, which operated limited-stop service in conjunction with existing local bus service on the same corridors, were 23% to 29% shorter relative to the local route, two-thirds of which was attributed to stopping less frequently (Skehan 2001).

A survey found that bus stop consolidation was most frequently cited as the "most successful action taken" to improve bus speeds (cited by eight out of 41 agencies responding to the question) (Boyle 2013).

Reliability Benefits

The reliability benefit of stop consolidation is not yet well-quantified, but it is believed to improve reliability since bus stopping patterns along a route will be more consistent from trip to trip (Kittelson & Associates et al. 2013).

Other Benefits

RTS (Regional Transit System in Gainesville, Florida) reported fewer motorist complaints due to being stuck behind stopped buses as a result of its stop consolidation program. It also reports that the money saved by not having to maintain as many stops can be used to upgrade the amenities of the remaining stops (Boyle 2013). Although some passengers may have to walk farther than before to get to or from a bus stop, their overall travel time is typically shorter due to their faster trip on the bus (Kittelson & Associates et al. 2013).

Cost Considerations

- **Planning and coordination costs.** Moderate to high, depending on the size of the effort (e.g., route versus system). Passenger volumes, stop spacing, and pedestrian infrastructure will need to be analyzed for each stop included in the study. The experience of transit agencies that have implemented stop consolidations is that a significant amount of public outreach is required to educate the public and local decision makers about the benefits of stop consolidation. Typically, some stops that had been slated for closure will be preserved based on community feedback. If the transit agency has not yet developed a formal bus stop spacing policy, doing so is a necessary first step.
- **Capital costs.** Low on a per-stop basis; consist of removing infrastructure (e.g., bus stop poles, shelter) from stops that are to be closed.
- **Maintenance costs.** Maintenance costs will be eliminated for the closed stops.
- **Bus operations costs.** Strategy reduces bus travel time and travel time variability. If elderly passengers and those with disabilities cannot or will not access the next-closest stop, they may switch to more costly paratransit service.
- **Other user costs.** On roadways without opportunities for motorists to pass stopped buses, motorists will experience fewer instances of having to stop and wait for a bus to serve passengers. Pavement damage due to bus stopping activity will cease at the closed stops. Current passengers whose stops are closed will have to walk farther to access a stop.

Implementation Examples

Examples of cities that have implemented bus stop consolidations are:

- Columbus, Ohio;
- Gainesville, Florida;
- Los Angeles, California;
- Portland, Oregon;

- San Francisco, California; and
- Spokane, Washington (Boyle 2013, Kittelson & Associates et al. 2013).

In addition, 30 of 59 transit agencies responding to a survey for *TCRP Synthesis 110* had consolidated stops to improve bus speeds.

Implementation Guidance

Bus stop consolidation is probably the single most effective strategy a transit agency can undertake on its own to improve bus speeds and reliability. A necessary first step is to adopt a formal, defensible stop spacing policy. AASHTO (2014) suggests that stop spacing should take into consideration "development density, street patterns, and the type of service operated," with suggested maximum spacing for local service of 400 ft in downtown areas, 660 ft in urban areas, and up to ¼ mile in suburban areas. However, a number of sources suggest longer typical stop spacing, as indicated in Table 7.

In general, when existing stop spacing is every block or two, block lengths are reasonably short (e.g., 250 ft or less), and adequate pedestrian infrastructure exists, the stop spacing can be increased up to a three-block spacing without requiring passengers to travel more than one extra block to access a bus stop, and with only a minimal reduction in the area served by the remaining stops.

Once a stop spacing policy has been adopted, attention can be turned to implementing it. One approach would be to select one route with relatively high ridership as a pilot project to demonstrate the benefits of stop consolidation. After a successful first project, the program could be expanded to other routes or the system as a whole. *TCRP Synthesis 110* (Boyle 2013) provides case studies of how transit agencies in Columbus, Ohio; Gainesville, Florida; and Spokane, Washington, have implemented stop consolidations, providing valuable lessons learned on the public outreach aspects of this type of project.

A flexible approach to applying stop spacing policy is also suggested. There will be situations where the locations of passenger trip generators, infrastructure constraints, and similar factors will suggest a different stop spacing than the typical spacing given in the policy. A flexible approach also allows the transit agency to respond to community concerns about stop closures by accommodating those concerns, where justified, or by presenting information showing the benefits of closing stops. This approach helps build goodwill within the community and support for future projects.

Additional Resources

- *Proposed Guidelines for Pedestrian Facilities in the Public Right-of-Way* (U.S. Access Board 2011)—design guidance for evaluating the accessibility of pedestrian routes to the next-closest stop.

Table 7. Example guidelines for typical bus stop spacing for local service.

	Location			
Source	**Downtown**	**Urban**	**Suburban**	**Rural**
Portland, Oregon (TriMet 2010)	780 ft	780 ft	1,000 ft	>1,000 ft
British Columbia, Canada (BC Transit 2010)	660 ft	750 ft	980 ft	1,250 ft
Florida DOT (2007) and *TCRP Report 19* (Texas Transportation Institute 1996)	600 ft	750 ft	1,000 ft	1,250 ft

- *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition (Kittelson & Associates et al. 2013)—Chapter 6 provides analytical methods for estimating the components of delay and dwell time associated with serving a bus stop.
- *TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds* (Boyle 2013)—implementation examples.

5.3 Route Design

Description

A route's alignment is adjusted to provide a faster, more direct trip from origin to destination for the majority of passengers.

Purpose

A routing that made sense in the past may not meet the needs of current passengers. Land uses may have changed, and the passenger demands that justified a diversion off a major street may no longer exist. Traffic patterns may have changed, and a turn that was once relatively easy for a bus to make may now involve considerable delay. Keeping buses on major streets allows them to take advantage of the reduced delays and potential signal progression provided on those streets. Revisiting the route design allows a transit agency to identify whether opportunities exist for streamlining the route without significantly compromising transit access.

Applications

Because adjusting a given route's alignment may affect service coverage and transfer opportunities to other routes, route designs are often evaluated on a system-wide basis as part of a comprehensive operations analysis or for a defined part of the system as part of a more-localized planning effort. However, route adjustments can also be undertaken on an individual route basis.

Companion Strategies

Route alignment changes may require stop relocations (Section 5.1), particularly at locations where the route currently turns. When it is not possible to relocate a turn, other strategies can be considered to minimize the delay at the turn. These include bus-only turn lanes (Section 6.1), passive signal timing changes (Section 6.4), phase reservice (Section 6.5), traffic signal shadowing (Section 6.6), transit signal priority (Section 6.7), bus-only signal phases (Section 6.9), and pre-signals (Section 6.11).

Constraints

The role of some bus routes in a transit system may be to meet service coverage needs rather than to provide quick, point-to-point service along a corridor, and it may be more difficult to make adjustments to these routes. Nevertheless, in these situations, it is still worthwhile to investigate whether providing more-direct routings that require a transfer would provide similar or better overall travel times. The constituency served by a route diversion may object to losing the diversion and having to walk farther to access service. Safe pedestrian infrastructure to the next-closest bus stop will need to exist for stops that are closed as a result of a route realignment.

Benefits

The time saved by eliminating route diversions and reducing delays caused by extra turns can be used to offset travel time increases due to traffic congestion or increased route patronage, to provide more schedule recovery time at the end of a route to combat reliability problems, to extend the route to provide more coverage with the same number of buses, or—when service is frequent and the time saved is large enough—to reduce the number of buses required to serve the route. These options are discussed in detail in Appendix B. Reducing the number of turns made typically reduces travel time variability.

A survey of 41 transit agencies found that route design changes were tied for second with transit signal priority (Section 6.7) as the "most successful action taken" to improve bus speeds (cited by six out 41 agencies) (Boyle 2013).

Cost Considerations

Since route realignments frequently involve stop relocations, the cost considerations listed in Section 5.1 also apply to route design changes.

- **Planning and coordination costs.** Moderate to high, depending on the size of the effort (e.g., route versus system). For diversions under study to be eliminated, the number of passengers benefiting from the diversion (i.e., boarding or alighting in that segment of the route) will need to be compared to the number of passengers not benefiting from the diversion (i.e., those already on board and not alighting in that segment of the route), along with their respective travel times. Turns in the route will require study to determine the magnitude of the existing delay (e.g., from field data collection or AVL data) and traffic analysis to determine the potential time savings from alternative routes. Outreach to passengers and other stakeholders that would be affected by changing the route is suggested.
- **Capital costs.** Relatively low on a per-stop basis; consist of removing infrastructure (e.g., bus stop poles, shelter) from stops that are to be closed and installing infrastructure at any new stops that are created (see Section 5.1).
- **Maintenance costs.** Bus stop maintenance costs may go up or down, depending on the net change in the number of stops resulting from the route realignment and any upgrades in stop amenities that are installed in conjunction with developing new bus stops.
- **Bus operations costs.** Strategy typically reduces route mileage and the number of stops made at intersections, which lowers the bus expenses related to these factors (e.g., fuel costs).
- **Other user costs.** Passengers using stops that will be closed will have to walk farther to access bus service, but passengers not served by a diversion will experience shorter travel times. The net effect on pavement damage will depend on the net change in the number of bus stops and the type of pavement provided at the stops.

Implementation Examples

A survey of 59 transit agencies found that 39 had streamlined one or more routes, with an average of 19% of the original route length being affected (Boyle 2013).

Implementation Guidance

A starting point for considering route design changes is to develop a route design policy if one does not already exist at the transit agency. Other transit agencies' policies can be consulted for guidance. The policy can be expressed as guiding principles for developing routes or can use more quantifiable measures, such as stating that route diversions should produce a net travel time benefit for passengers or setting a maximum value for the route mileage divided by the straight-line distance from end to end. Having and following a route design policy can make it easier to justify and explain route design changes to passengers affected by changes. Extensive changes to the route design may require a service equity evaluation under FTA Title VI (FTA 2012).

It is beyond the scope of this guidebook to further discuss transit route design; however, Walker (2012) uses layman's language to explain the issues involved with designing transit routes from both the transit agency and passenger perspectives.

Additional Resources

- *Highway Capacity Manual 2010* (Transportation Research Board 2010)—analytical methods for estimating the delay associated with turns at signalized and unsignalized intersections.
- *Human Transit* (Walker 2012)—several chapters discuss route design concepts.
- *TCRP Report 113: Using Archived AVL-APC Data to Improve Transit Performance and Management* (Furth et al. 2006)—Section 4.4.6 covers the use of AVL data to analyze speed and delay issues; Section 4.7 covers the use of APC data to analyze passenger demand, which is useful for quantifying the potential impact to passengers of route changes.

5.4 Fare Payment Changes

Description

Changes are made in how or where bus fares are paid, with the intent of reducing the time required to pay fares. Some types of fare payment changes are implemented in conjunction with all-door boarding, which further speeds up the boarding process.

Purpose

Dwell times can be a significant direct component of a bus's overall travel time along a route. In addition, when dwell times are long enough to cause a bus to fall out of the traffic signal progression provided along a street, they can lead to the bus experiencing traffic signal delay.

As discussed in the Benefits subsection, different fare payment methods involve widely different service times, both within a given fare payment method (e.g., cash payment with coins versus cash payment with bills and coins) and between fare payment methods (e.g., proof of payment versus magnetic stripe card) (Kittelson & Associates et al. 2013). Saving 2 s or more per passenger, when multiplied by the number of boarding passengers per trip, can result in significant time savings, particularly when traffic signal delays can be avoided at high-volume stops.

In addition, certain kinds of fare payment methods can allow multiple passengers to board at once, which also speeds up the boarding process. For example, when buses have wide front doors that allow two passengers to board at once, one door channel can be used for passengers needing to use the farebox, while the other channel can be used for passengers with flash passes. Off-board fare payment, when combined with a proof-of-payment fare inspection system, can allow boarding passengers to use any door to board, which is the fastest boarding scenario of all.

Applications

Off-board fare payment is often a feature of BRT service but can also be considered for any route or stop experiencing high passenger volumes. When having bus drivers check the fare of every passenger is a transit policy or public relations necessity, it can still be possible to provide fare machines at the busiest bus stops, thereby shifting the most time-consuming part of the boarding process (purchasing the fare) off the bus; passengers simply show their receipts when boarding. New, faster fare payment technologies can be considered as existing farebox equipment reaches the end of its functional life, or they can be offered as a new option (e.g., ticketing via mobile phone) in addition to existing options. Pricing (e.g., substantial discounts) can be used to encourage greater use of prepaid fare media such as ticket books or bus passes.

Companion Strategies

Changes to the fare payment process are typically implemented as stand-alone changes, either as part of a system-wide change, as a feature of premium bus service, or in response to high passenger demands on specific routes or at specific stops.

Constraints

Potential issues to be addressed with any change to the fare payment system include costs (capital, operating, and maintenance) and enforcement, particularly when considering off-board fare collection and proof-of-payment systems. Costs are discussed in the Cost Considerations subsection, while guidance on addressing fare enforcement is available in some of the references listed in the Additional Resources section. Vandalism of ticket vending machines may be a concern.

An environmental justice or fare equity analysis may need to be performed when changing fares or the method of paying a fare (FTA 2012).

Benefits

A change in the fare payment method can result in shorter times for passengers to board a bus. Table 8 provides typical per-passenger boarding values along with ranges of service times provided in the literature. The fastest method is simply to board with no interaction with the bus operator, as happens in a proof-of-payment system. The next fastest method is to present a fare payment receipt (e.g., pass, transfer, receipt from an off-board fare machine, mobile phone display) for inspection. The passenger boarding times associated with fare payment methods that

Table 8. Passenger boarding times by fare payment method (level boarding).

	Average Passenger Service Time (s/p)	
Situation	**Observed Range**	**Typical**
No fare payment	1.75–2.5	1.75
Visual inspection (paper transfer/flash pass/mobile phone)	1.6–2.6	2.0
Single ticket or token into farebox	2.9–5.1	3.0
Exact change into farebox	3.1–8.4	4.5
Mechanical ticket validator	3.5–4.0	4.0
Magnetic stripe card	3.7–6.5	5.0
Smart card	2.5–3.2	2.75

Source: *TCRP Report 165* (Kittelson & Associates et al. 2013), Exhibit 6-4. Note: s/p = seconds per passenger.

Table 9. Spreading of passengers between door channels with multiple-channel boarding.

Available Door Channels	Percent Passengers Through the Busiest Door Channel	
	Boarding	Alighting
2	60%	75%
3	45%	45%
4	35%	35%
6	25%	25%

Source: *TCRP Report 165* (Kittelson & Associates et al. 2013), Exhibit 6-58.

require interacting with a farebox increase with (1) increasing complexity of the transaction (e.g., inserting multiple bills) and (2) increasing likelihood of having to redo part of the process (e.g., reinserting a rejected bill, reswiping a magnetic stripe card).

Proof-of-payment fare systems allow passengers to use all available doors to board. Passengers will not divide themselves evenly between each door, but a substantial reduction in overall boarding times will result nevertheless. Table 9 indicates the percentage of passengers using the busiest door channel with all-door boarding compared to boarding through a single door channel. (A door channel is one lane entering or exiting a door; thus a wide door that allows two people in or out at once provides two door channels.) One transit agency responding to a survey reported a 9% travel time savings from a combination of off-board fare payment and all-door boarding (Boyle 2013). A study of a BRT line in Seattle found that travel times through a 5-mile corridor improved by 10% to 16% (2 to 3.5 min) after off-board fare payment and all-door boarding was implemented in conjunction with headway changes (Ryus et al. 2015).

As with any strategy involving spot locations, the dwell time saved at a given bus stop may in some cases be lost at the next traffic signal since the bus simply arrives at the traffic signal earlier and waits longer. Therefore, the total time savings along a route or street as a direct result of reduced dwell time will typically be less than the sum of the dwell time savings from individual stops (see Section 4.4). However, because buses will sometimes also be able to make green lights that they otherwise would have missed if the dwell time had been longer, an additional indirect benefit is the opportunity to avoid traffic signal delay at some intersections, which will also serve to reduce overall bus travel times. This potential signal delay avoidance depends on such factors as the traffic signal timing, average dwell time, and the variability of dwell times, and thus no simple answer can be provided. Appendix C of the TCRP Project A-39 final report (*TCRP Web-Only Document 66*), building on work by St. Jacques and Levinson (1997), describes an analytical method for estimating the likelihood that a bus will be able to make the green light at a downstream signal.

Cost Considerations

- **Planning and coordination costs.** Moderate to high, depending on the size of the effort (e.g., route versus system). Introducing new fare payment technology (e.g., smart cards, mobile ticketing), off-board fare payment, or proof of payment may involve a feasibility study, an implementation plan (including planning for new staff functions such as fare inspectors), a pilot project, environmental justice or fare equity studies, and customer outreach, among other actions. Locating ticket machines on bus stop platforms may require coordination with the local roadway agency.
- **Capital costs.** Moderate to high, depending on the number of buses or bus stops involved. Per-unit costs for off-board ticket vending machines used for BRT systems ranged from $25,000 to $60,000 in 2009, and were higher with a smart-card option. More than one machine

may be required at high-volume stops or for redundancy when no onboard fare payment option is provided. Additional centralized hardware may be required for a complete system. When used with a proof-of-payment system, some fare payment options (e.g., smart cards, magnetic stripe cards) require special equipment for fare inspectors to check that the fare has been paid and has not expired (Diaz and Hinebaugh 2009).

- **Maintenance costs.** It is estimated that one full-time employee is required for every 25 ticket vending machines to maintain them. Parts and training will be required for new equipment (Diaz and Hinebaugh 2009).
- **Bus operations costs.** Potential new and ongoing costs include those for staff to collect money from ticket vending machines (one full-time employee per 25 machines), security staff, fare inspectors (for proof of payment), and software licenses for the fare collection system, as well as electrical and communications costs for off-board fare equipment (Diaz and Hinebaugh 2009).
- **Other user costs.** The impacts of fare payment changes are mostly limited to the transit agency and its passengers. To the extent that motorists are delayed by stopped buses and dwell time is reduced as a result of the fare payment changes, motorists could also benefit from the changes.

Implementation Examples

- Nine transit agencies responding to a survey had implemented proof of payment on their BRT routes (Larwin and Koprowski 2012).
- Eight transit agencies responding to a survey (two of which operated BRT) had implemented off-board fare collection, six allowed all-door boarding on selected high-volume routes, and one (San Francisco Muni) allowed all-door boarding on all routes (Boyle 2013).
- Twenty-two transit agencies responding to a survey used pricing to encourage greater use of prepaid fare media (Boyle 2013).

Implementation Guidance

There are four main approaches to making changes to how fares are paid when the objective is to reduce dwell times and improve bus speeds. In order of easiest to hardest, these are:

- **Encourage greater use of prepaid fare media.** This approach has the lowest capital costs. However, the trade-off will need to be assessed between the potential operational benefit and the possible loss of revenue if bigger discounts are used to encourage greater prepaid media use. The magnitude of the benefit will depend on the current level of prepaid fare media usage, the willingness of passengers to make larger prepaid purchases, and the attractiveness of the prepaid options compared to paying a fare for each trip. The entire system will benefit to some degree.
- **Off-board fare collection.** This approach has shown benefits for high-volume BRT routes but may not be cost-effective for lower-volume routes (Larwin and Koprowski 2012). The cost of installing, maintaining, and operating ticket vending machines will need to be weighed against the operational benefits of reducing dwell time. Off-board fare collection can be implemented without proof of payment, with passengers showing their fare receipt to the bus operator.
- **Proof of payment with all-door boarding.** This approach offers the greatest potential time savings but requires careful attention to fare enforcement, both to protect fare revenue and to avoid perceptions that too many passengers are not paying their fares. Fare inspectors help provide a security presence onboard vehicles and at stations, which may improve passengers' perceptions of security while using transit (Larwin and Koprowski 2012). All of the issues relating to off-board fare collection also relate to all-door boarding.
- **Changes in fare collection technology.** This is the longest-term approach because of the costs involved and the system-wide impact. Dwell time reductions will be realized to the

extent that passengers switch to the new technology from a slower fare payment method; technologies that are convenient to use and offer a financial incentive for their use will be more attractive to passengers. The entire system will benefit to some degree. Some technologies, such as smart cards, provide the potential for obtaining useful information about how passengers use the transit system, which can assist the transit agency with its planning efforts (Multisystems et al. 2003).

Additional Resources

- *TCRP Report 94: Fare Policies, Structures, and Technologies: Update*—information and guidance on developing fare policies and structures, with 13 case studies on a range of fare initiatives (Multisystems et al. 2003).
- *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition (Kittelson & Associates et al. 2013)—Chapter 6 provides analytical methods for estimating the change in dwell time that would result from changes in fare payment methods, mix of fare payment media used, or number of doors available for boarding; contains analytical methods for estimating the change in average bus speeds resulting from changes in dwell time.
- *TCRP Synthesis 96: Off-Board Fare Payment Using Proof-of-Payment Verification*—lessons learned from proof-of-payment implementations, including information on addressing fare evasion concerns, with seven case studies (Larwin and Koprowski 2012).

5.5 Vehicle or Equipment Changes

Description

The type of bus used on a route or the equipment used on a bus is changed to allow passengers to board and alight faster, to provide improved interior circulation, to improve vehicle performance, to use more-direct routings, or a combination of these.

Purpose

Buses and their equipment can be changed in a variety of ways that can affect bus travel times:

- **Larger buses.** Larger buses (e.g., articulated, double-deck) can be employed on a route to address increasing ridership and mitigate crowding occurring inside the bus that slows boarding (e.g., waiting for passengers to move to the back of the bus) or alighting (e.g., difficulty getting past people in the aisle to get to the exit door). Articulated buses generally provide space for more doors.
- **Smaller buses.** Smaller buses can be employed on lower-volume routes as a way to use streets or to make turns that larger vehicles cannot, thus allowing more-direct routings.
- **More and/or wider doors.** More door channels allow passengers to enter and exit the bus more quickly (Kittelson & Associates et al. 2013).
- **Low-floor buses.** Low-floor buses allow passengers to enter and exit more quickly than high-floor buses due to the lack of stairs. Wheelchair ramps on low-floor buses deploy more quickly than wheelchair lifts on high-floor buses (Kittelson & Associates et al. 2013).
- **Changed seating configuration.** Seats can be removed (e.g., 2 + 1 seating) or realigned (e.g., perimeter seating) to provide a larger aisle for standees and more room for passenger

circulation at stops. Seats can also be selectively removed to provide storage areas for strollers, luggage, and so forth (Boyle 2013).
- **Higher-performance buses.** Hybrid buses, for example, offer better acceleration and hill-climbing ability than comparably sized diesel buses (Boyle 2013), which may offer significant travel time savings on routes with many stops that travel through hilly terrain.

Applications

Changes to bus models (including equipment) are typically made as part of a transit agency's normal vehicle replacement program (i.e., replacing buses that have reached the end of their useful lives), in response to increases in service, or as part of the introduction of specialized or premium bus services (e.g., BRT). Therefore, the benefits of the change may require a period of years to reach full effect or may be limited to specific routes (e.g., BRT routes).

Companion Strategies

The introduction of larger buses may require lengthening bus stops (Section 7.2). Providing more or wider doors helps support fare payment strategies that allow the use of multiple doors or door channels (Section 5.4). Measures that reduce the number of times buses must stop along the route, such as stop relocation (Section 5.1), stop consolidation (Section 5.2), route design (Section 5.3), transit signal priority (Section 6.7), and bus lanes (Section 8.1), help offset the slower acceleration associated with larger buses.

Constraints

Changes to bus models and equipment need to be coordinated with potential changes to maintenance facilities to accommodate the new models or equipment with maintenance staff training and the need to stock new or more spare parts.

Introducing longer buses may require that existing bus stops be lengthened, which may affect on-street parking or require changes to bus pullouts. Longer buses accelerate more slowly than conventional 40-ft buses, which will offset at least some of their potential time savings benefits.

Reducing the number of seats will provide more interior room for standing passengers but will reduce the overall quality of service that passengers experience. Perimeter or longitudinal (i.e., facing the aisle) seats may be perceived as less comfortable than seats that face forward.

An environmental justice or service equity analysis may need to be performed associated with the use of new and improved bus models (FTA 2012).

Benefits

- **Larger buses.** To the extent that the number of standees is reduced, dwell time can be reduced. Boarding takes an average 0.5 s longer per passenger when standees are present (Kittelson & Associates et al. 2013); alighting times may also be increased if passengers have trouble getting to an exit door due to crowded aisles.
- **Smaller buses.** The potential benefit is the difference in travel time that could be achieved via a more direct route accessible with the smaller bus relative to a less direct route usable by a larger bus.
- **More and/or wider doors.** More doors or door channels allow more passengers to board and alight simultaneously, thus reducing dwell times. See Table 9 for typical values of door usage.

- **Low-floor buses.** Boarding and alighting takes an average 0.5 s less per passenger on low-floor buses compared to high-floor buses (Kittelson & Associates et al. 2013).
- **Changed seating configuration.** To the extent that interior circulation is improved, boarding and alighting times may decrease, thus improving dwell time, but research is lacking to quantify the magnitude of this effect.
- **Higher-performance buses.** To the extent a new bus model offers better performance than the current bus model and that the route characteristics (e.g., large number of stops made, hills) are well-suited to higher-performance buses, running time improvements between stops can be realized.

Cost Considerations

- **Planning and coordination costs.** New vehicles can have low incremental costs since speed- and delay-related factors would normally become additional evaluation criteria when selecting a particular bus model and equipment to order.
- **Capital costs.** New vehicles can have a variety of incremental costs relative to the existing bus type (e.g., size, propulsion system, amenities), depending on the type of bus being considered. Costs may be more fairly compared on a per-seat or per-passenger basis rather than a per-vehicle basis. Existing bus maintenance facilities may need to be altered to accommodate larger buses if they are not already accommodated by the facility design (Hemily and King 2008).
- **Maintenance costs.** New bus models will require training for maintenance staff and new spare parts inventories. Larger (e.g., articulated) buses have more components and greater per-vehicle maintenance costs relative to standard buses (Hemily and King 2008).
- **Bus operations costs.** Larger buses will have poorer fuel economy than comparable standard buses. If larger buses are being used to maintain hourly passenger capacity on a route while using fewer buses, labor costs will decrease (fewer bus operators required), but dwell times will increase (more boarding passengers per stop per bus due to longer headways), which will tend to increase bus travel times.
- **Other user costs.** The impacts of changes to vehicle types are mostly limited to the transit agency and its passengers.

Implementation Examples

A survey of 59 transit agencies found that many had implemented some form of vehicle type or equipment change as a way to improve bus speeds:

- Introduced or increased the use of low-floor buses: 33.
- Introduced or increased the use of different-sized vehicles (including paratransit vehicles): 22.
- Introduced better-performing vehicles: 17.
- Changed seating configurations: 8.
- Changed door configurations: 4 (Boyle 2013).

Implementation Guidance

Because of their slower acceleration, longer buses are better suited from a speed perspective for routes where buses do not have to stop as often (e.g., limited-stop or BRT routes). Implementing strategies that help reduce the number of times a bus must stop due to traffic congestion or traffic control can help offset the impact of slower acceleration on bus speeds. When larger buses are used to serve the same number of passengers using fewer buses, dwell times will increase unless other strategies (e.g., all-door boarding or other fare payment changes) are used to offset the increased passenger boarding and alighting volumes per bus (Hemily and King 2008).

Anticipating the future use of different types of buses than those currently used when planning new maintenance facilities greatly facilitates the eventual introduction of those buses since the facilities do not require expensive modifications at a later date (Hemily and King 2008).

Additional Resources

- *TCRP Synthesis 75: Uses of Higher Capacity Buses in Transit Service* (Hemily and King 2008)—transit agency experiences with introducing larger buses into service.
- *TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds* (Boyle 2013)—implementation examples.

CHAPTER 6

Traffic Control Strategy Toolbox

This chapter is the second of four toolbox chapters presenting potential strategies for improving bus speeds and reliability. The strategies presented in this chapter require the participation of the roadway agencies responsible for traffic control devices, and sometimes other agencies, but are generally less infrastructure-intensive than the strategies presented in the following two chapters.

This chapter defines and discusses the following strategies:

- Allowing buses to make movements (e.g., left turns) prohibited to other vehicles,
- Restricting the ability of other vehicles to make turns,
- Yield to bus,
- Passive traffic signal timing adjustments,
- Phase reservice,
- Traffic signal shadowing,
- Transit signal priority,
- Transit signal faces,
- Bus-only signal phases,
- Queue jumps,
- Pre-signals,
- Traffic signal installed specifically for buses, and
- Traffic control enforcement.

The introduction to Chapter 5 describes how each strategy section is organized.

6.1 Movement Restriction Exemption

Description

Buses are allowed to make movements (e.g., left turns, right turns, proceed straight ahead) that are prohibited for other vehicles.

Purpose

Turning movements may be prohibited for a number of reasons, including:

- A signalized intersection has insufficient capacity to provide a left-turn phase for general traffic;
- A street has insufficient space to provide a left- or right-turn lane, and vehicles waiting to make turns would excessively delay vehicles behind them;

- Roadway agency access management policies exist that divert left-turn movements to signalized intersections;
- Boulevard-type street treatments with raised landscaped medians exist that prevent left turns; and
- Allowing vehicles to make the turn could generate undesired through traffic within a neighborhood or district.

At the same time, allowing buses to make these movements may allow a more direct routing that would save travel time or provide bus service closer to passengers' origins and destinations.

Applications

Applications are in locations where the most direct bus routing is not feasible because of a turn prohibition for traffic operations reasons (e.g., delays to through traffic, cut-through traffic prevention), as opposed to prohibitions for safety reasons (e.g., previous intersection crash experience) or one-way street patterns, and where street widening is infeasible.

Companion Strategies

At unsignalized intersections, if the turn prohibition is due to a lack of gaps in the opposing traffic, and a traffic signal exists a relatively short distance downstream of the intersection, traffic signal shadowing (Section 6.6) may be an option for creating a gap. When a turn lane is provided for bus use only, red-colored pavement (Section 7.4) may be considered to help reinforce the bus-only message. Periodic enforcement (Section 6.13) may be required to maintain motorist respect for the traffic control. At signalized intersections, bus-only signal phases (Section 6.9) are suggested to be considered in conjunction with a turn exemption, potentially supplemented with transit signal priority (Section 6.7), transit signal faces (Section 6.8), or both. Exemptions from right-turn requirements are commonly used with queue jump (Section 6.10) and queue bypass (Section 8.6) strategies.

Constraints

- The turn prohibition may have been installed because of safety concerns that would also apply to bus movements.
- The more frequent the bus service, the greater the potential delay to other traffic.
- Neighborhoods may fear that allowing buses into the neighborhood will encourage other vehicles to make the turn illegally or will open the door to eventually allowing all traffic to use the street.
- A formal exception to a roadway agency's access management policy may need to be requested.

Benefits

Buses will save travel time equivalent to the difference in travel time via the existing routing and the travel time possible via the proposed routing. The magnitude of the benefit is highly site-specific but can be estimated by a traffic analysis.

Cost Considerations

- **Planning and coordination costs.** Moderate. A traffic engineering study will be required to evaluate the traffic and bus operations impacts of the proposed change and to evaluate potential safety issues. A formal request for an exception to the roadway agency's access management policy may be required. If infrastructure is being modified (e.g., creating a median opening for a bus-only turn lane), design plans will need to be developed.

- **Capital costs.** Low to moderate, depending on the specific site characteristics. Some sites may require only replacing the existing signs; other sites may require changes to pavement markings, traffic signal heads, or curb lines and medians.
- **Maintenance costs.** Low incremental costs typically. If a painted bus lane treatment (Section 7.4) is used, the paint may need to be restored more frequently than other pavement markings.
- **Bus operations costs.** Lower costs due to shorter distances traveled as well as potential savings from the travel time reduction achieved.
- **Other user costs.** Depending on how the strategy is implemented, other traffic may not be affected (e.g., the bus waits in its own turn lane at an unsignalized location) or may experience additional delay (e.g., extra time required to serve the bus left-turn phase at the signal, delay waiting behind a bus waiting for a gap in traffic to make its turn). The magnitude of these delays would be determined through the traffic engineering study.

Implementation Examples

OC Transpo has installed bus-only left-turn lanes at key intersections where there is insufficient capacity to serve automobile left turns. At an intersection where right turns would be blocked by pedestrians, right turns are prohibited, but buses on a route that turns right are allowed to make the turn. At a T-intersection with a two-lane approach (left-turn lane and right-turn lane), buses are allowed to make a left turn from the right-turn lane as a form of a queue bypass (Section 8.6). A "Bus Excepted" plaque on the lane-usage sign is used to indicate the allowed bus use.

Portland, Oregon, provides a bus-only left-turn lane at a busy, complex intersection where there is insufficient capacity to serve automobile left turns.

Implementation Guidance

It is suggested that the transit agency first discuss the reason(s) behind the existing turn prohibition with the roadway agency since this will help focus the scope for a traffic engineering study to determine the feasibility of making a change for buses. Delay impacts are suggested to be quantified on both a vehicle-delay and person-delay basis.

If the turn prohibition was implemented as part of a neighborhood traffic-calming program, it is suggested to meet with the neighborhood to identify potential concerns with allowing bus access into the neighborhood, present the benefits of doing so, and identify potential mitigation needs, including helping pay for enforcement if it turns out to be necessary. The community's experience with traffic-calming measures can be relevant in assessing whether motorists can be expected to generally respect the traffic control and thus whether enforcement will be required. If a jurisdiction has no experience with signing-only violation rates for traffic-calming or transit-preferential strategies, it would be prudent to plan in advance for an enhanced level of enforcement if the violation rate turns out to be unacceptably high to stakeholders. See also Section 6.13.

Additional Resources

- *Access Management Application Guidelines* (Dixon et al., no date)—a companion to TRB's *Access Management Manual* (Williams et al. 2014) that provides guidance on and case studies of incorporating multimodal considerations, including bus transit, into roadway agencies' access management programs. Not yet published.
- *Highway Capacity Manual 2010* (Transportation Research Board 2010)—analytical methods for estimating the delay associated with turns at signalized and unsignalized intersections.

6.2 Turn Restrictions

Description

One or more existing general traffic turning movements at an intersection are prohibited.

Purpose

Turning movements at intersections can cause delay for buses and other intersection users when:

- No turn lane is available, and vehicles wishing to continue straight must wait for a vehicle to make its turn before they can proceed;
- Protected left-turn phases (i.e., left-turn arrows) are provided at a traffic signal since each additional signal phase adds additional lost time—time unusable by vehicles at the start of green and during a portion of the yellow and all-red intervals—and therefore delay (Urbanik et al. 2015); and
- Turning volumes are small relative to through volumes, and the road space used by a turn lane could be more efficiently used to serve other bus or other general traffic movements, thus reducing overall delay.

Selectively prohibiting turning movements can free up time or roadway space for use by buses and traffic in general.

Applications

Intersections where relatively low turning volumes share a lane with through traffic, and where the turning traffic experiences relatively high delays (e.g., waiting for a gap in oncoming traffic [left turns], waiting for pedestrians to finish crossing a crosswalk [right turns]), are good candidates for this strategy. In these cases, relatively few motorists will be inconvenienced, while many other roadway users will benefit.

In order to free up sufficient intersection capacity to keep the intersection operating acceptably following construction of a bus lane, bus lane projects (Section 8.1) that take a travel lane may require turning movement prohibitions at intersections currently operating near capacity.

Intersections where the queue in a turn lane spills over into the adjacent through lane, and the turn lane cannot be lengthened, and intersections experiencing high crash rates due to turning movements are also potential candidates for this strategy.

Turning prohibitions can be implemented full time or only during peak periods.

Companion Strategies

To avoid the need for an indirect routing, buses can be exempted from the turn prohibition (Section 6.1). To eliminate delays to buses caused by right-turning vehicles, the strategy can be applied with queue jumps (Section 6.10) and queue bypasses (Section 8.6). It may also be needed for contraflow (Section 8.8) and reversible (Section 8.9) bus lanes to prevent potential conflicts between buses and vehicles turning across the bus lane. Right turns by large vehicles (e.g., trucks) may need to be prohibited if curb extensions (Section 7.5) would reduce the available turning area too much. Right-turn prohibitions help make curbside bus lanes (Section 8.2) operate more effectively. Enforcement (Section 6.13) may be required to ensure that only buses make the restricted turn.

Constraints

A key consideration is the availability of a suitable alternate route for the diverted traffic. Suitability criteria can include traffic operations, safety, compatibility with adjacent land uses, and diversion distance. The displaced turns may be accommodated as left turns or U-turns at upstream or downstream intersections, by alternative intersection forms (e.g., jug-handle intersections), or by requiring traffic to travel around the block, making three right turns (AASHTO 2014). Guide signs may be necessary to communicate the desired diversion route(s) to motorists or to advise of the turn prohibition in advance of the intersection.

Benefits

The magnitude of the delay benefit from a turn prohibition is highly site-specific but can be estimated through a traffic analysis. Archived AVL data can be used to identify locations along a route where buses experience delay and determine the magnitude of those delays (Furth et al. 2006).

Turn prohibitions can also produce safety benefits. For example, New York City's evaluation of Select Bus Service on Webster Avenue in the Bronx identified that left-turn prohibitions at selected intersections not only helped traffic operations, they also addressed issues with left-turning crashes and conflicts between turning vehicles and pedestrians in the crosswalk (New York City DOT and MTA-NYCT 2014). To the extent that crashes are reduced, travel time variability due to crash-caused congestion can also be reduced. Prohibiting right turns eliminates conflicts between turning vehicles and bicyclists and pedestrians.

Cost Considerations

- **Planning and coordination costs.** Moderate. A traffic engineering study will be required to evaluate the traffic and bus operations impacts of the proposed change, including for the streets and intersections likely to be used by diverted traffic, and to evaluate how intersection safety could be affected. If it appears that a turn prohibition may induce neighborhood cut-through traffic as motorists seek out alternate routes, additional planning for mitigation measures may be required along with conducting outreach to the neighborhood.
- **Capital costs.** Typically relatively low, depending on the specific site characteristics. Some sites may simply require posting turn-prohibition signs; others may require new guide signs, changes to pavement markings, or removal of left-turn traffic signal heads.
- **Maintenance costs.** Typically minor impacts associated with maintaining the extra signs that are required.
- **Bus operations costs.** Potential savings from reductions in travel time and travel time variability.
- **Other user costs.** At a minimum, this strategy will normally reduce delay to through traffic at the intersection and, depending on how it is implemented, may also benefit other traffic movements at the intersection. The reduced delay will typically more than offset any increased travel time experienced by the diverted traffic in cases where through traffic volumes are high relative to the diverted traffic volumes. In addition, crashes associated with the prohibited turning movement should be greatly reduced, although crashes along the diversion route may go up due to the increased traffic volume. In addition, intersection delays along the diversion route may increase as a result of the increased traffic volume caused by diverted traffic.

Implementation Examples

A total of nine of 59 agencies responding to a survey had implemented left-turn, right-turn, or (in one case) through-movement restrictions (Boyle 2013).

Implementation Guidance

A traffic engineering study will be necessary to quantify the impact of the proposed change on bus and general traffic operations and on safety. Delay impacts are suggested to be quantified on both a vehicle-delay and person-delay basis.

AASHTO (2014) recommends prohibiting left turns when vehicles turning left would need to share a lane with through traffic because they "reduce capacity about 50 percent, delay through-vehicles, and tend to increase crashes."

Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.3.2.2 addresses turning movement controls.
- *Highway Capacity Manual 2010* (Transportation Research Board 2010)—analytical methods for estimating the delay associated with turns at signalized and unsignalized intersections.
- *Highway Safety Manual* (AASHTO 2010)—analytical methods for estimating the effect of traffic control and roadway geometry changes on crashes.

6.3 Yield to Bus

Description

Motorists are required by law, or are encouraged through bus-mounted signs, to let buses back into traffic when they are signaling to exit a bus stop.

Purpose

To reduce the reentry delay experienced by buses that have finished serving passengers but then need to wait for a gap in traffic to continue on their route.

Applications

Yield-to-bus strategies are implemented as agency-wide measures. In states and provinces with yield-to-bus laws, the law specifies how motorists are to be notified—typically via a sticker mounted on the left rear of the bus or through a flashing or illuminated sign mounted on the left rear of the bus. Some states and provinces only apply the law to lower-speed roadways (i.e., speed limits under 35 mph). In locations without yield-to-bus laws, "Please Yield," "Thanks for the Brake," or a similar slogan is used on a sticker or rear advertising panel to encourage motorists to let buses back in (King 2003).

Companion Strategies

The strategy is implemented as a stand-alone measure, with periodic enforcement (Section 6.13) desirable. Installing curb extensions (Section 7.5) achieves the same purpose.

Constraints

To be enforceable, state legislation needs to be passed to require motorists to yield to buses exiting stops. The experience of transit agencies that take advantage of yield-to-bus laws has been that they are rarely enforced and that they might see larger benefits if they were more regularly enforced. Whether a suggestion or a legal requirement, an outreach campaign may be necessary to raise public awareness of the issue.

Benefits

Any benefit from a yield-to-bus strategy will occur at locations where the bus stops out of the traffic lane since buses normally do not have to wait for other traffic when they stop in the traffic lane (unless a queue exists). The potential benefit from yield to bus is high since reentry delay can range from 1 to 12 s, depending on traffic volumes, at bus stops well away (i.e., at least ¼ mile downstream) from traffic signals, and can be considerably higher at stops at or near signals (Kittelson & Associates et al. 2013). A Florida study recorded average reentry delays of over 30 s at some bus stops (Zhou et al. 2011).

In practice, little documented benefit has been found, although some agencies have reported success with long-standing public campaigns. One study found that six of 16 agencies responding to a survey felt that yield to bus had helped schedule reliability somewhat (King 2003). However, an observational study in Florida found almost no instances of motorists yielding to buses except when traffic was queued; that study did note that, unlike other states, Florida did not require transit agencies to conduct public relations campaigns prior to using yield-to-bus stickers (Zhou et al. 2011). Both studies found a transit agency and bus operator preference for electronic signs over stickers or decals.

Motorists appear to be most willing to yield when traffic speeds are low (25 mph or less), with compliance increasing as speeds decrease to stop-and-go conditions. Transit agencies have generally not reported any issues with increased accidents related to buses pulling into traffic following the implementation of yield-to-bus laws (King 2003).

Cost Considerations

- **Planning and coordination costs.** Moderate to high. If a yield-to-bus law is desired and does not currently exist, some effort will be necessary to convince the state legislature to pass such a law. Transit agency experience has been that, whether a request or a legal requirement, yield to bus is more effective when accompanied by a public awareness campaign; some agencies have spent up to $250,000 to $350,000 on such campaigns (King 2003).
- **Capital costs.** Low on a per-vehicle basis, particularly when stickers are used, but add up when the entire bus fleet is equipped.
- **Maintenance costs.** Electronic yield signs will require extra maintenance.
- **Bus operations costs.** Potential savings from reductions in travel time. Although not quantified to date, travel time variability may increase if no one yields prior to yield to bus and some begin to yield following yield to bus.
- **Other user costs.** Motorists who yield (and those behind them) will experience small delays as they allow buses back into traffic.

Implementation Examples

As of 2011, seven states (California, Colorado, Florida, Minnesota, New Jersey, Oregon, and Washington) and two Canadian provinces (British Columbia and Quebec) had passed yield-to-bus laws (Zhou et al. 2011).

Implementation Guidance

It is not necessary to have a yield-to-bus law in place to see benefits from a public awareness campaign; a "Thanks for the Brake" campaign that started in Vancouver more than 35 years ago and was adopted across British Columbia is reported to have "been highly successful in nurturing a more friendly and courteous environment between bus operators and motorists" (King 2003). Bus drivers blink their four-way lights or give a wave out their window as thanks when motorists let them back in.

The literature reports that yield-to-bus laws are generally not enforced by the police; therefore, transit agencies may need to consider funding occasional enforcement efforts, combined with public awareness campaigns, to see meaningful benefits from yield-to-bus laws.

Additional Resources

- *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition (Kittelson & Associates et al. 2013)—Chapter 6 provides analytical methods for estimating the magnitude of reentry delay.
- *TCRP Synthesis 49: Yield to Bus—State of the Practice* (King 2003)—review of transit agency experiences with yield to bus.

6.4 Passive Traffic Signal Timing Adjustments

Description

Existing signal timing plans are optimized to reduce delay for traffic in general on intersection approaches used by buses or for buses specifically. Since the signal timing is followed whether or not a bus is present, the adjustments are considered to be passive.

Purpose

Signal timing that worked well when the timing plans were originally developed may become less effective over time due to a variety of reasons (Urbanik et al. 2015):

- Changes in traffic volumes,
- Changes in traffic patterns (e.g., length of the peak periods, vehicle mix),
- Changes in roadway geometry (e.g., new turn lane, relocated bus stop), and
- Changes in pedestrian volumes (e.g., resulting from new development in the area).

Therefore, reviewing existing signal timing is an activity that roadway agencies should undertake on a periodic or ongoing basis, although they may not always do so due to a lack of resources or other reasons. Optimizing traffic signal timing is done to achieve desired roadway agency goals such as minimizing the number of stops or traffic signal delays experienced by vehicles traveling along a street. Changes that result in better operations for automobiles may also benefit buses, although good signal timing for automobiles is not necessarily good signal timing for buses.

Signal timing can also be adjusted specifically to benefit buses. Some of these changes, such as shorter cycle lengths or more green time for the approaches used by buses, will also improve operations for many other roadway users. Other changes, such as signal timing designed to allow buses to progress, may benefit some modes and disbenefit others.

Applications

Typical passive traffic signal timing adjustments that benefit buses include:

- Signal retiming in a corridor to reduce delay to through traffic, including buses;
- Reducing intersection cycle lengths to reduce the amount of delay experienced by buses when they do have to stop for a red signal; and

- Allocating more green time to approaches used by buses (which can potentially include minor-street approaches and left-turn lanes).

Companion Strategies

Passive traffic signal timing adjustments can be implemented in conjunction with other signal timing strategies that react to the presence of a bus, including phase reservice (Section 6.5), transit signal priority (Section 6.7), bus-only signal phases (Section 6.9), queue jumps (Section 6.10), and pre-signals (Section 6.11).

Constraints

The amount of signal time that can be reallocated to approaches served by buses will be constrained by the amount of time required to serve vehicles on other approaches (dependent on traffic volumes and the number of lanes) and by the minimum time required to serve pedestrian movements (dependent on the crossing width and the minimum pedestrian walk times specified in the MUTCD and roadway agency policy).

In corridors where the signals are coordinated (i.e., operate as group, allowing traffic movements to be synchronized between intersections), a common cycle length will be used. Making a change to one intersection's cycle length will normally require all of the other intersections' cycle lengths to be changed identically. (A potential exception is an intersection that can operate acceptably with a cycle length that is half that of the other coordinated intersections, thus providing a green twice as often as the other intersections—an operation known as *double cycling.*) Thus, the operations of all the coordinated intersections will need to be considered when considering changing the cycle length (Urbanik et al. 2015).

Benefits

The potential benefit from signal timing adjustments will depend on the quality of the existing timing and intersection- and corridor-specific conditions that include traffic volumes, traffic patterns, vehicle mix, and traffic signal spacing, among others. Transit signal priority benefits reported in the literature tend to be greater in cases when traffic signals had not been recently retimed, suggesting that retiming signals on a regular basis is an action that will provide benefits both to transit and general traffic. *NCHRP Report 812: Signal Timing Manual* (Urbanik et al. 2015) describes tools available for timing signals and determining the effects on multimodal operations.

In general, a shorter cycle length will reduce delay for buses and pedestrians, as long as the intersection can continue to operate under capacity. Delay experienced by vehicles and bicyclists may go up or down. Allocating more green time to intersection approaches used by buses will reduce delay for motorized vehicles, bicyclists, and (potentially) pedestrians on those approaches, but will increase delay to motorized vehicles and bicyclists on the approaches whose green time is shortened. (Side-street pedestrian delay will only increase if its walk time is reduced or the cycle length increased, but often only the minimum walk time is provided, to allow the signal to stop serving the side street when no side-street vehicles remain to be served).

Timing traffic signals to allow buses to progress, accounting for typical dwell times at stops, can significantly reduce the traffic signal delays and extra stops experienced by buses but will likely increase the delay experienced by motorized vehicles on the intersection approaches used by buses. It is thought that bicyclists may also benefit from bus signal progression in some cases since the two modes have similar average speeds in urban (non-downtown) conditions, but research is lacking in this area.

Cost Considerations

- **Planning and coordination costs.** Moderate for a corridor, requiring collecting traffic demand data at each intersection (including for buses, bicyclists, and pedestrians) along with existing signal timing, using an appropriate set of tools to develop an initial timing plan and to evaluate the effects of that plan, and finally, implementing and adjusting the final plan in the field. Bus operators can be a good source of information about intersections or corridors where signal timing improvements may be useful.
- **Capital costs.** No change.
- **Maintenance costs.** No change.
- **Bus operations costs.** Potential savings from reductions in traffic signal delay. Timing signals to allow buses to progress can also help reduce bus travel time variability.
- **Other user costs.** Potential changes in delay (both up and down) for other intersection users, as discussed in the Benefits section; however, the outcome should be an overall improvement on a person-delay basis.

Implementation Examples

TCRP Synthesis 110 reports that 14 of 59 transit agencies responding to a survey had experienced traffic signal timing changes. Seven of these agencies measured the impact on bus speeds, with three experiencing 5% to 10% increases in speeds, three experiencing 0% to 5% increases in speeds, and one experiencing a decrease in speeds after the traffic signal cycle length was increased. Three of the 14 transit agencies reported that they had a formal process in place with one or more roadway agencies to raise potential signal timing issues and that the roadway agencies generally made changes when feasible. San Francisco has changed traffic signal timing to allow buses to progress on two corridors; Ottawa times its traffic signals to allow buses to progress through downtown (Boyle 2013). OC Transpo staff evaluate intersection operations to identify whether shorter signal cycles or more green time for bus movements can be accommodated. Many transit signal priority implementations reported in the literature included traffic signal timing optimization (see *TCRP Web-Only Document 66*).

Implementation Guidance

It is suggested that transit agencies develop both an internal process for identifying and reporting signal timing issues that affect bus operations (e.g., bus operator reporting) and a formal process with their roadway agency partners for submitting those issues for investigation and potential action.

Transit agencies may wish to consider proposing (and potentially funding) a pilot project on a major bus corridor to make signal timing improvements for buses, including evaluating the effects on bus operations and other roadway users. A successful pilot project can lead to increased attention on the part of the roadway agency to considering bus operations needs when retiming traffic signals.

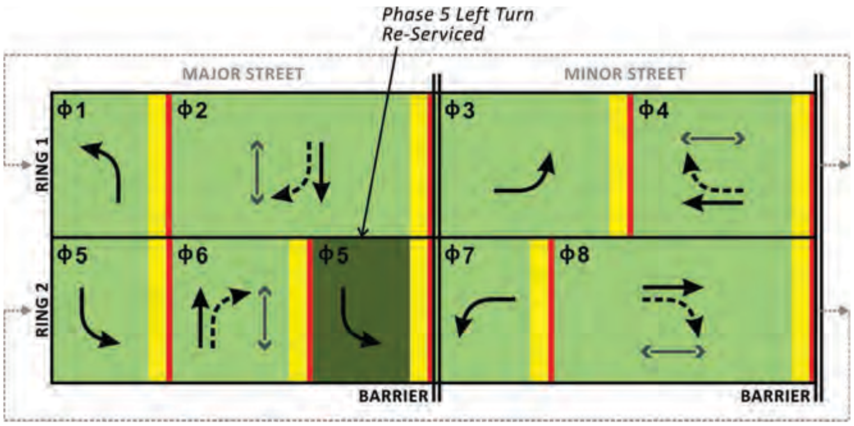
Signal progression for buses is a potential strategy for high-passenger-volume corridors where a net person-delay benefit may be feasible. It can also be considered in communities that wish to prioritize non-automobile traffic.

Additional Resources

- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—Section 4E.05 addresses pedestrian signal timing requirements.

- *NCHRP Report 812: Signal Timing Manual*, 2nd Edition (Urbanik et al. 2015)—presents traffic signal and signal timing concepts, provides guidance on developing signal timing plans, and describes tools for timing signals and estimating the impacts of signal timing plans.

6.5 Phase Reservice



Description

A traffic signal phase is served twice during a traffic signal cycle—for example, a left-turn phase that is served both at the start and the end of the green phase for through traffic.

Purpose

Serving a phase twice per cycle minimizes the time a bus has to wait to be served and thereby reduces bus travel time variability. It accommodates varying bus arrival times at a traffic signal (e.g., caused by varying dwell times at an upstream stop) better than serving a phase only once per cycle.

Applications

Potential applications for phase reservice to benefit buses are:

- Serving peak-direction major-street bus left turns during peak periods on roadways that have highly directional traffic flows (e.g., mostly inbound toward downtown in the morning);
- Serving major-street bus left turns or bus movements on minor-street or driveway approaches (e.g., serving transit centers or park-and-rides) to the traffic signal during periods of low to moderate volumes on the major street;
- As a substitute for double cycling (see Section 6.4, Constraints) at minor intersections, when half the normal cycle length would not produce good operations; and
- Serving special bus phases (Section 6.9) or queue jumps (Section 6.10) (Urbanik et al. 2015, Corby et al. 2013).

Phase reservice can be made conditional on the presence of a bus or a predetermined number of vehicles.

Companion Strategies

Phase reservice can be considered in conjunction with special bus phases (Section 6.9) or queue jumps (Section 6.10).

Constraints

Phase reservice is an advanced feature that may not be provided by the intersection's current traffic signal controller. This strategy requires that underutilized green time be available within the traffic signal cycle that can be used to reserve a phase (e.g., relatively low traffic volumes in the opposite direction of travel when reserving a left-turn phase).

Benefits

Bus delay will be reduced, as will the delay experienced by other vehicles sharing the intersection approach. The amount of time saved will be site-specific, but average movement delay reductions in the range of 10 to 30 s have been reported in the literature (e.g., Corey et al. 2013, Lavrenz et al. 2015). Bus travel time variability will also be reduced, although this is more difficult to quantify without a fairly extensive simulation model that includes upstream and downstream intersections.

Cost Considerations

Many costs are dependent on whether a new signal controller would be required.

- **Planning and coordination costs.** Relatively low for an intersection equipped with a suitable controller, requiring collecting traffic demand data at each intersection (including for buses, bicyclists, and pedestrians) along with existing signal timing, evaluating the effects of phase reservice on intersection operations, and implementing in the field. Moderate when a new signal controller is required.
- **Capital costs.** Potentially no change if a suitable controller already exists; moderate if a new controller will be required. Some additional vehicle detection capability may be required to implement phase reservice conditionally, which entails relatively low costs.
- **Maintenance costs.** No change unless a new controller is required and it is the roadway agency's first advanced controller, in which case staff training will be required.
- **Bus operations costs.** Potential savings from reductions in traffic signal delay and bus travel time variability.
- **Other user costs.** Phases whose green times are shortened to provide phase reservice will experience greater vehicle delay. A net vehicle-delay benefit will be more likely to occur as traffic volumes served by the reserved phase increase and as traffic volumes served by the phase(s) with reduced green time decrease (Corey et al. 2013). Pedestrian crossing delay will increase on the crosswalk conflicting with a reserved left-turn phase if its walk time is reduced.

Implementation Examples

Ottawa has applied conditional phase reservice. When two to three cars or a bus occupy a left-turn lane, the left turn is served twice within the cycle, both as a leading left turn and as a lagging left turn. This strategy was already being used for non-transit applications (clearing queues of cars), so no special negotiating was needed with the city transportation department to use it for buses, subject to the normal checks that there was sufficient capacity available to accommodate the extra interval. City staff have not observed any driver expectancy issues with the use of this treatment. It is only used during the morning peak period (6 a.m. to 9 a.m.). Copenhagen, Denmark, uses phase reservice at a few intersections to provide queue jumps before and after parallel traffic is served.

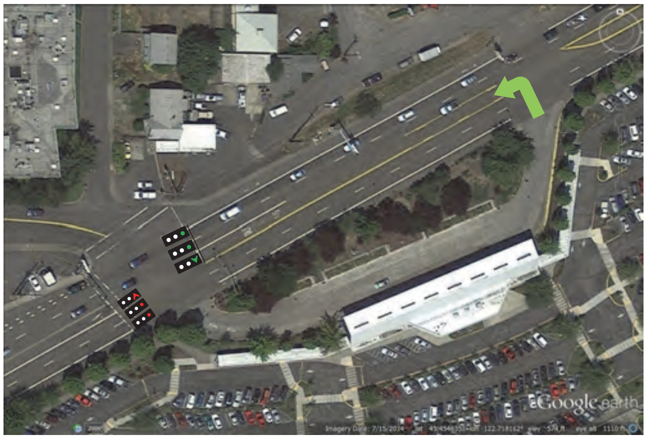
Implementation Guidance

In a transit context, this strategy has greatest potential application to signalized intersections where buses turn left.

Additional Resources

- *NCHRP Report 812: Signal Timing Manual* (Urbanik et al. 2015)—Sections 9.2.3 and 12.3.1.4 address phase reservice.

6.6 Traffic Signal Shadowing



Source: © 2015 Google

Description

A bus wishing to turn left at an unsignalized intersection triggers a call for a left-turn phase at a nearby downstream intersection, thereby creating a gap in traffic that the bus can use to turn left.

Purpose

When opposing traffic volumes are sufficiently high, and right-turning traffic from driveways or the downstream cross street fill available gaps before a bus can use them, buses may experience significant delays waiting to turn left at an unsignalized location.

Applications

Left turns from a major street or left turns out of a minor street or driveway at an unsignalized intersection. Examples include those at transit centers, park-and-ride lots, and shopping centers. Figure 2 illustrates the process for a left turn from a major street into a cross street; a similar process can be used for turns from a minor street into a major street.

In Figure 2 (1), a bus arrives at the unsignalized intersection and is blocked from making a left turn by oncoming traffic. The bus is detected in the left-turn bay (e.g., using a transponder or video detection, or a normal loop detector if only buses are allowed to make the turn) and a call is placed for the left-turn phase at the downstream intersection, even when no vehicles are waiting to make the left turn.

In Figure 2 (2), the left-turn call is served, stopping the flow of oncoming traffic in the process. Right turns on red need to be prohibited on the cross street at the traffic signal to ensure that a gap is formed. The right-turn-on-red prohibition can be permanent or can be implemented only when needed by activating a blank-out sign.

In Figure 2 (3), the gap has reached the unsignalized intersection and the bus can make its turn.

Companion Strategies

This strategy can be used in conjunction with turn restrictions (Section 6.2); for example, a bus-only turn into a transit center or park-and-ride lot. It can also be combined with transit signal priority (Section 6.7) to serve the left-turn phase sooner than usual.

Traffic signal shadowing is considered only as a strategy because the MUTCD does not currently provide warrants for traffic signals installed specifically for buses (Section 6.12). In most cases, a traffic signal would be the more straightforward option and could also serve other needs, such as providing a safer pedestrian crossing opportunity on busy streets that have a long distance between traffic signals.

Constraints

This strategy requires a nearby downstream traffic signal that provides a protected left-turn phase (i.e., left-turn arrow), the ability to prohibit right turns on red from the cross street at that traffic signal, no or few driveways between the traffic signal and the unsignalized intersection, and a means of detecting buses. The ability to serve the left-turn phase early is constrained by the requirement to provide a minimum pedestrian crossing time on the conflicting crosswalk.

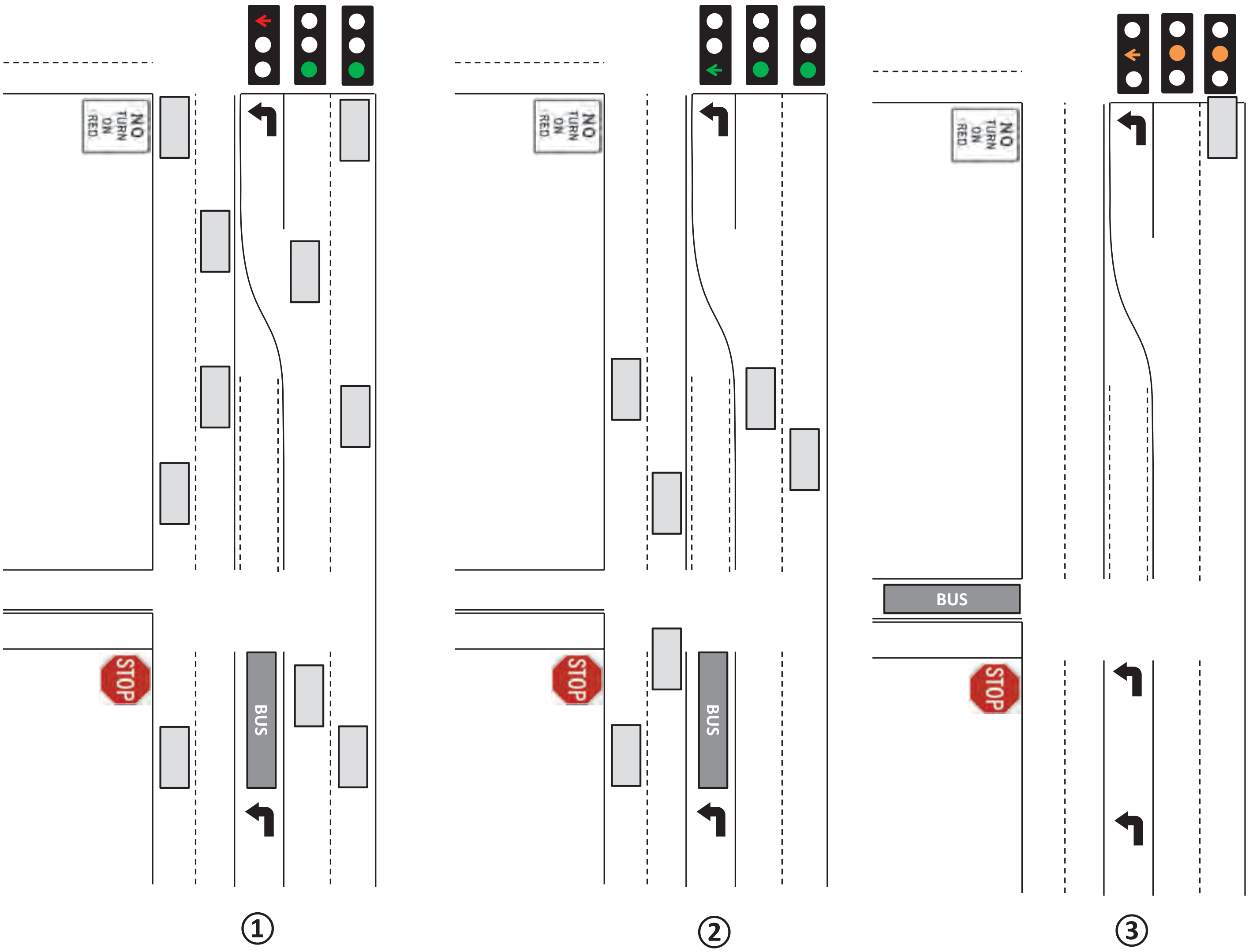


Figure 2. Example of traffic signal shadowing.

Benefits

The delay benefit to buses is site-specific and would need to be determined from a traffic engineering study.

Cost Considerations

- **Planning and coordination costs.** Moderate. A traffic engineering study is needed to determine whether shadowing is the most appropriate strategy and what the impacts would be. If the strategy is determined to be feasible, design plans would need to be developed for the detection connection to the downstream traffic signal.
- **Capital costs.** Moderate. A means will be needed to detect the bus, and those detections will need to be communicated to the signal controller at the downstream traffic signal.
- **Maintenance costs.** Small increase in costs related to the detection system.
- **Bus operations costs.** Potential savings from reductions in traffic signal delay and bus travel time variability.

- **Other user costs.** Delay may be increased for traffic from the opposite direction if no left-turning vehicles would have needed to be served or when the left-turn phase is served earlier than normal. Prohibiting right turns on red may increase delay for that movement if gaps in traffic and pedestrian crosswalk activity would have otherwise permitted right turns on red to occur. Calling a left-turn phase early may increase pedestrian delay on the conflicting crosswalk if the crosswalk's walk time is reduced as a result.

Implementation Examples

TriMet uses traffic signal shadowing at the Barbur Transit Center in Portland, Oregon. The signalized intersection includes the bus entrance to the transit center, while the unsignalized intersection is the bus exit. When buses need to leave, the left-turn phase is called at the upstream traffic signal, creating a gap in northbound traffic that right-turning buses can use immediately. If a gap also happens to exist in southbound traffic, left-turning buses can complete their turn immediately; otherwise, they can pull into a center two-way left-turn lane and wait for a gap in southbound traffic before proceeding. No right-turn-on-red prohibition is required in this instance because the transit center driveway is a one-way entrance to the transit center from the traffic signal.

Calgary and Edmonton, Canada, use a form of traffic signal shadowing at certain intersections with half signals (i.e., where pedestrian crosswalks are signalized at an intersection, but cross-street traffic is stop-controlled). When a bus arrives at the intersection, the pedestrian crossing phase is called, whether or not pedestrians are present, creating a gap in traffic that the bus can use to turn onto the main street. However, this approach is not currently permitted by the MUTCD since half signals are not allowed.

Implementation Guidance

Before pursuing traffic signal shadowing as an option, first consider whether other solutions to the problem are feasible. Would a traffic signal be warranted at the location for general traffic reasons (e.g., the pedestrian volume, coordinated signal system, or crash experience warrants)? Can the bus route use a different set of streets to avoid the unsignalized intersection?

The following characteristics make a site a potential candidate for a traffic signal shadowing treatment:

- Traffic volumes that create substantial delay for turning buses;
- Presence of a nearby traffic signal with a left-turn phase that can create a gap in traffic;
- Ability for the traffic signal controller to distinguish buses from other turning traffic;
- No driveways or only low-volume driveways located between the traffic signal and the location where bus turns occur so that other vehicles do not fill the gap that is created;
- Low pedestrian and bicycle activity so that these road users in most cases do not prevent buses from using the gap that is created; and
- For left turns from a cross street onto a major street, existence of a two-way left-turn lane or similar refuge area that buses can use as needed to complete their turns in two stages.

The Transportation Association of Canada guidelines suggest using, in situations where traffic signal shadowing might be used, a "traffic signal required by transit" (Section 6.12) installed solely to serve transit needs that might not be justified by general traffic needs (Corby et al. 2013). The guidelines note that not all Canadian jurisdictions may permit a traffic signal for transit purposes and also note that some Canadian jurisdictions permit the use of half signals that serve both pedestrian and transit needs. As discussed in Section 6.12, at the time of writing, a provision for traffic signals required by buses was being considered for inclusion in a future edition of the MUTCD.

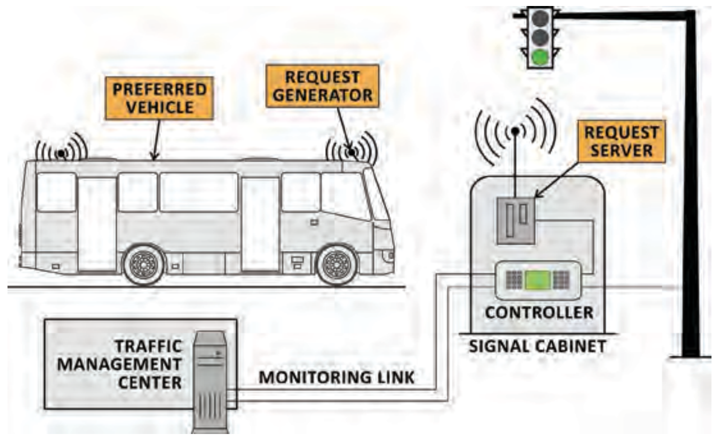
Additional Resources

- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—information on how and where traffic signals, transit signals, and pedestrian hybrid beacons may be used (Parts 4 and 8).

6.7 Transit Signal Priority

Description

Traffic signal timing is altered in response to a request from a bus so that the bus experiences no or reduced delay passing through the intersection.



Purpose

Traffic signal delay contributes significantly to slower bus speeds and greater travel time variability, particularly with greater numbers of traffic signals encountered along a route and with longer cycle lengths (i.e., longer waiting times) at those signals. TSP strategies are designed to reduce traffic signal impacts on bus travel speeds and travel time variability.

Applications

Transit signal priority can be applied in several ways:

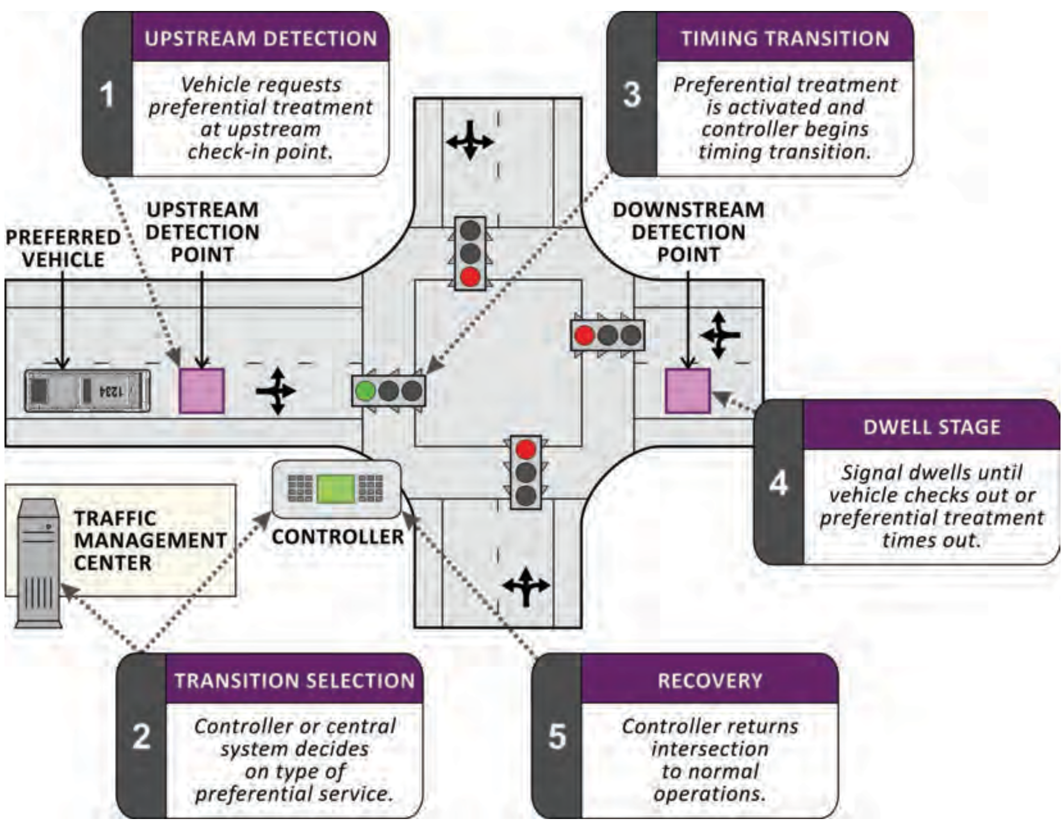
- **Green (phase) extension.** If a bus is detected close to the end of the green phase for the bus's intersection approach, the green phase is extended to allow the bus to pass through the intersection, thus allowing the bus to avoid a lengthy delay waiting for the next green. Depending on how TSP is implemented and the bus detection capabilities provided, the length of the extension can be a fixed amount for every bus, or the extension can be ended when it is detected that the bus has cleared the intersection.
- **Red truncation (early green).** If a bus is detected stopped at the intersection, conflicting phases (e.g., the side-street green) are ended early, and a green is provided to the bus's approach sooner than would have occurred otherwise, thus reducing the amount of delay the bus experiences.
- **Phase insertion.** A special phase is provided to serve the bus when it is detected. This application is typically used in conjunction with turn lanes serving buses only (e.g., a left turn into a transit center—see Section 6.1, Movement Restriction Exemption), special bus phases serving nonstandard movements (Section 6.9), and queue jumps (Section 6.10).
- **Sequence change.** The order in which phases are served is altered to serve the bus sooner than would occur otherwise. For example, a lagging left-turn phase can be switched to a leading left-turn phase when a bus is detected.
- **Phase skipping.** Phases are skipped (i.e., not served) so that service can return to the phase serving the bus more quickly (Urbanik et al. 2015).

Depending on the capabilities of the traffic signal controller, more than one of these applications can be implemented at a given intersection.

Two key aspects of each of these TSP applications are that (1) signal timing changes are made within the context of the normal signal timing plan, and (2) priority may not necessarily be granted to a bus making a request. A related strategy, transit signal preemption, was used early on as a transit-preferential strategy. However, because preemption interrupts the normal signal timing plan to immediately serve a specific request for service, it interrupts any traffic signal coordination that might be provided, can cause significant delays to other intersection users, and can terminate pedestrian phases while pedestrians are still crossing the intersection. As a result, preemption is generally used today only in conjunction with railroad crossings, drawbridges, and emergency vehicles. Priority is typically used to serve buses, trucks, and other preferred vehicles since it maintains signal coordination and provides minimum pedestrian crossing time, thereby producing much smaller impacts on intersection operations (Urbanik et al. 2015).

Chapter 10 of the *NCHRP Report 812: Signal Timing Manual* (Urbanik et al. 2015) provides details about how each TSP application can be implemented; there are various ways to generate a request for service, detect bus locations, and process service requests. The general process is described as follows, and is illustrated in Figure 3:

- **Upstream detection.** Either the traffic signal system detects the bus's presence directly, or the bus is aware of its position and sends a request for service at an appropriate time.
- **Transition selection.** The signal controller or the central system receives the request and decides how or whether to serve it, depending on when in the traffic signal cycle the request is received and whether higher-priority requests have been received. If the request is granted, the controller or central system decides how best to implement it, based on a number of factors (e.g., cycle length, traffic detected on other approaches, provision of minimum pedestrian phase lengths) that can potentially be programmed by the roadway agency.



Source: Urbanik et al. (2015).

Figure 3. Transit signal priority process.

- **Timing transition.** Changes to the signal timing are implemented to serve the request as soon as safely and operationally feasible.
- **Dwell stage.** The priority request continues to be served until (1) the bus is detected at a downstream location or (2) the maximum time allotted for serving the priority request has expired. Other phases that do not conflict with the priority phase can also be served.
- **Recovery.** The signal timing is adjusted to restore normal operations as soon as safely and operationally feasible. Depending on how TSP is implemented, normal operations can resume as soon as the next cycle; in other cases, it may take several cycles.

Requests for priority can be made, prioritized, and granted based on a variety of conditions, including:

- **Schedule** (e.g., late buses are granted priority; on-time or early buses are not);
- **Bus status** (e.g., in service or out of service, door open or door closed, on route or off route);
- **Direction of travel** (e.g., peak direction or off-peak direction);
- **Passenger load** (e.g., buses with more passengers can be prioritized);
- **Level of priority** (e.g., BRT or frequent-service routes versus low-frequency routes, emergency vehicles versus buses); and
- **Number of cycles since the previous granting of priority** (if more than one cycle is needed for the intersection to recover to normal operations) (Urbanik et al. 2015).

The degree to which a traffic signal controller can prioritize requests (if at all) depends on the controller's capabilities; advanced controllers provide much more flexibility. When buses initiate priority requests themselves, some of the intelligence can be placed onboard the bus (e.g., bus status and schedule adherence information) and used in deciding whether to make a priority request.

Companion Strategies

The potential need for stop relocations (Section 5.1) should be considered when implementing TSP since some applications work better with some stop locations than with others (e.g., green extension with far-side stops); see the Implementation Guidance subsection for more information. TSP can also be combined with most signal-related strategies, including passive signal timing adjustments (Section 6.4), traffic signal shadowing (Section 6.6), bus-only signal phases (Section 6.9), turn lanes serving buses only (Section 6.1), queue jumps (Section 6.10), and pre-signals (Section 6.11).

Constraints

Implementing TSP can be a significant capital investment because traffic signal controllers may need to be upgraded, bus detection capabilities at intersections may need to be improved, and (depending on the type of system implemented) equipment may need to be provided onboard a portion or all of the bus fleet.

A key requirement for TSP to be successful is that buses actually be able to reach the intersection to take advantage of it. If an intersection approach operates over capacity, it may make matters worse to adjust the signal timing when the bus is blocked by other vehicles since the bus cannot get to the intersection and may not be granted priority again until the signal recovers from the first granting of priority. Pre-signals (Section 6.11) can be considered to manage queues at an intersection and give buses unrestricted access to the intersection while continuing to serve as many other vehicles on the approach as possible, given the over-capacity conditions.

As with other strategies that reduce signal delay at individual intersections, the overall effectiveness of TSP is typically less than the sum of the individual intersection delay savings because in some cases the bus will simply arrive early at the next traffic signal and wait (see Section 4.4). As discussed in the Benefits section, in some instances no significant travel time benefit has been achieved on a corridor basis. In other cases, TSP has been quite successful at improving bus speeds. Therefore, because this strategy's potential costs are significantly higher than those of most other transit-supportive roadway strategies, prior to committing to implement TSP, it is particularly important to evaluate the potential benefit of it in the context of the signal controller capabilities that will be provided, the traffic signal spacing, bus stop locations, and other corridor characteristics.

Granting signal priority to buses may require changes in state traffic laws or administrative rules. Specific applications, such as phase skipping, might not be permitted by state or local policy.

Benefits

A challenge with evaluating implemented TSP projects is that they are usually implemented in conjunction with other transit-supportive roadway strategies, and it is difficult from field studies to separate out the impact of TSP relative to (for example) signal timing plan optimization or bus stop relocation unless each strategy is implemented sequentially. Therefore, simulation is often relied on to evaluate the specific impact of TSP on bus travel times.

TCRP Project A-39 simulated the effects of a number of strategies, including TSP, at an isolated intersection. With a near-side stop, providing up to 10 s of green extension or red truncation (TSP) in the peak direction reduced average bus delay by 3, 3, and 10 s and average vehicle delay on the approach by <1, 1, and 2 s, with intersection *v/c* ratios of 0.5, 0.8, and 1.0, respectively. With a far-side stop, TSP reduced average bus delay by 3, 4, and 6 s and average vehicle delay by <1, 1, and 3 s for the same *v/c* ratios. Implementing TSP in both directions resulted in similar or slightly worse results for bus delay and generally substantially worse results for vehicle delay. The best package of strategies was to move a near-side stop to the far side and implement TSP in one direction, which provided average time savings of 6 to 15 s for buses and 1 to 3 s for vehicles on the same intersection approach. Cesme et al. (2015) found similar results via simulation, with 4- to 12-s average bus delay savings with 10 s of green extension or red truncation, and 6 to 18 s of savings with 15 s of green extension or red truncation.

However, when TCRP Project A-39 simulated providing up to 10 s of green extension and red truncation along a 1.3-mile-long corridor with nine traffic signals, average bus travel times through the corridor were only reduced by 9 s in the best-case scenario (TSP applied at all signals), or an average of 1 s per intersection. When TSP was implemented at just the three moderate-volume intersections (those with *v/c* ratios of between 0.6 and 0.9), corridor travel times were reduced by about 7.5 s, or an average of 2.5 s per intersection. Implementing TSP at moderate-volume intersections and at all intersections resulted in 8% and 9% reductions in travel time variability, respectively (Ryus et al. 2015).

Turning to actual transit agency implementations of TSP, Smith et al. (2005) present eight case studies of TSP. In six cases, bus travel times through a corridor decreased by 9% to 16%; in the other two cases, no significant travel time reductions were observed, but travel time variability decreased. Gardner et al. (2009) provide similar data for 12 international cities. In eight cities, average bus travel times decreased by 4% to 19% (and up to 24% in one specific corridor). In four cities, there was no significant change in bus travel times, but travel time variability decreased in three of those cities. Reductions in travel time variability were also observed in four other cities that did not quantify changes in bus travel times. Studies of TSP in Portland, Oregon (Kimpel et al. 2005, Smith et al. 2005, Koonce et al. 2006) have found limited travel time savings from TSP, but did find travel time variability improvements.

The reasons why TSP does not always provide travel time benefits have not been well-quantified to date, but potential reasons include:

- Too few priority calls, whether due to too-restrictive conditions (e.g., high thresholds for being behind schedule) or incorrect programming of the priority logic in the signal controller;
- No change made to bus schedules to take advantage of potentially faster travel times, thus locking the scheduled travel time in place but reducing the number of late buses;
- Locations for detecting the bus located inappropriately for the selected TSP application (e.g., providing priority for buses still serving passengers at a near-side stop);
- Too much traffic congestion, so that buses could not take advantage of any priority granted;
- Not enough traffic congestion, so that buses experienced relatively little delay at signals prior to implementing TSP; and
- Signal spacing too frequent, so that time saved at one intersection was spent waiting at a downstream intersection, with no net change in travel time (Gardner et al. 2009, Albright and Figliozzi 2012, Feng et al. 2015, Ryus et al. 2015).

Both simulation results and actual implementations have found that TSP typically reduces delay for traffic on the intersection approaches used by buses (typically the major-street approaches) and produces negligible to minor increases in side-street delay (Smith et al. 2005, Ryus et al. 2015).

Cost Considerations

- **Planning and coordination costs.** Moderate to high. Traffic demand data need to be collected for each intersection (including for buses, bicyclists, and pedestrians) along with existing signal timing, the logic for granting priority needs to be determined (if not already developed by prior implementations), an initial timing plan needs to be developed and evaluated, and the final plan needs to be implemented and adjusted in the field. If TSP is a new strategy for the roadway agency or the transit agency, the TSP infrastructure will need to be planned and designed. Performing a simulation study of corridor operations with and without TSP is suggested.
- **Capital costs.** Variable, depending on how TSP is to be implemented and how much of the required infrastructure already exists (e.g., the roadway agency has already installed advanced signal controllers for other reasons), but is typically high when starting from scratch.
- **Maintenance costs.** Variable, depending on how TSP is to be implemented and how much of the required infrastructure already exists. Roadway agency costs will likely increase; transit agency costs will also increase when some of the TSP infrastructure is placed on buses. There will also be staff training costs associated with introducing TSP to a jurisdiction.
- **Bus operations costs.** Bus travel time variability is typically reduced. Depending on how TSP is implemented (e.g., schedules adjusted or not) and corridor-specific conditions, there may also be a reduction in bus travel times.
- **Other user costs.** Vehicular traffic on the approaches served by TSP will typically experience a small average delay reduction due to TSP, while vehicular traffic on the approaches not served by TSP will typically experience a negligible to small delay increase. If the cycle time and pedestrian walk times are not changed, pedestrian delay will be unchanged. Phase skipping can significantly increase vehicular and pedestrian delay for those approaches that are skipped.

Implementation Examples

TSP has been implemented on a large scale in Houston, Texas; Sacramento and Los Angeles, California; and Portland, Oregon, among other cities. It has also been implemented on one or more corridors (including many BRT routes) in numerous other cities; Smith et al. (2005) identified at least 24 transit agencies that had implemented TSP at the time of their research.

Implementation Guidance

As discussed in the Benefits section, TSP does not always provide a significant corridor-level travel time benefit. There it is suggested that the transit agency first investigate lower-cost, quicker-to-implement strategies that may provide as great or greater benefits than TSP. In particular, stop relocations (Section 5.1), stop consolidations (Section 5.2), and passive traffic signal timing adjustments (Section 6.4) offer good potential for time savings. An exception to this guidance would be when a transit agency is developing a BRT project; in this case, TSP becomes one component of a major investment project.

Interviews conducted for TCRP Project A-39 showed that roadway agency staff were often concerned about the possible impact of TSP on traffic and pedestrian operations. Successful approaches that transit agencies took to overcome these perceptions included:

- Commissioning a traffic analysis to evaluate corridor operations with TSP in place,
- Lending spare TSP equipment to roadway agency staff to experiment with in their signal shops, and
- Taking roadway agency staff on study trips to meet with their peers in cities with similar TSP implementations to learn from their experiences.

Fire departments may also be concerned that providing signal priority for buses may interfere with priority operations for emergency vehicles; in these cases, ensuring that the system is capable of prioritizing emergency vehicles over buses can overcome these concerns. If traffic signals do not currently have the ability for emergency vehicle preemption, then upgrading traffic signals to serve both buses and emergency vehicles can generate stakeholder support for the project.

Interviews conducted for TCRP Project A-39 showed that successful first experiences with TSP paved the way for an expansion of its use on subsequent projects.

The following characteristics make a corridor more suitable for TSP:

- Peak-period intersection *v/c* ratios of between 0.6 and 0.9, such that intersections operate below capacity but with sufficient traffic demand that buses experience significant delays at traffic signals;
- High existing transit ridership or the potential for higher ridership with service improvements;
- Sufficient bus volumes to justify the investment, but not so high that TSP would be called nearly every cycle (in which case, passively adjusting the signal timing to provide an equivalent benefit would be more appropriate); in general, corridors with at least four buses per hour per direction; and
- Primarily far-side bus stops or stops that can be relocated to the far side (AASHTO 2014, Ryus et al. 2015).

Note that these characteristics are guidelines and not hard-and-fast rules. For example, intersections with relatively low *v/c* ratios may still benefit from TSP if the street is wide and minimum pedestrian crossing times dictate a long cycle length, with the result that buses experience considerable delay when they must stop for a red light at times when cross-street pedestrians are present. If traffic signals are already TSP-capable (for example, to serve emergency vehicles), then the relatively low incremental cost of implementing TSP may justify doing so at all signals in the corridor or on corridors with lower bus volumes.

Other considerations related to TSP are:

- Providing TSP only in the peak direction provides similar bus delay savings but better general traffic delay savings than providing it in both directions.
- Conditional application of TSP allows the system to be used more effectively—for example, by only granting priority to late buses, by prioritizing routes at intersections with bus service on both streets, and by prioritizing buses on the basis of passenger loads.

- Adjust the schedule to take advantage of any time savings provided by TSP; otherwise, giving priority only to late buses will lock the existing bus travel time in place. In this respect, TSP is well-suited for routes with headway-based schedules since conditional TSP can be configured to maintain bus headways while still providing a speed benefit.
- TSP implementations that change the order in which pedestrian crosswalks are served (e.g., phase skipping, sequence change) can be confusing for visually impaired pedestrians. Accessible pedestrian signals are suggested to be used to indicate to these pedestrians when their crosswalk is being served. Note that the U.S. Access Board's Proposed Guidelines for Pedestrian Facilities in the Public Right-of-Way (2011) would require accessible pedestrian signals to be installed in any event at an existing signal when the signal controller and software are altered, which is often the case when TSP is implemented.

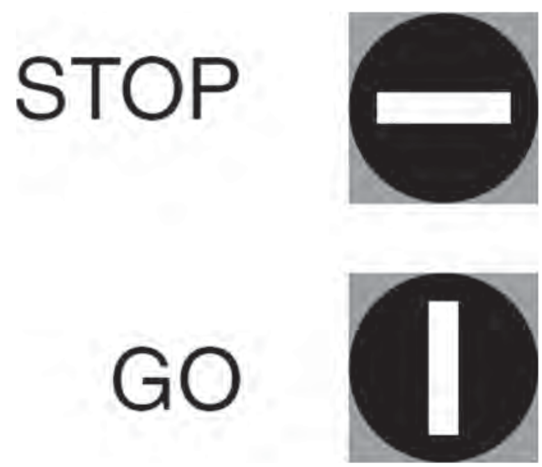
Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.8.1 covers transit signal operations for transit priority.
- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—Section 4D.27 addresses priority control of traffic signals.
- *NCHRP Report 812: Signal Timing Manual* (Urbanik et al. 2015)—Chapter 10 addresses traffic signal priority in general and transit signal priority specifically, from the signal timing standpoint.
- *Transit Signal Priority (TSP): A Planning and Implementation Handbook* (Smith et al. 2005)—presentation of a systems engineering approach to planning, designing, and implementing TSP, suggested roles and responsibilities for stakeholders in a TSP system, and case study implementation examples.

6.8 Transit Signal Faces

Description

Special traffic signal faces (displays) used for controlling bus, streetcar, or light rail operations.



Purpose

Transit signals can help reduce the possibility that road users will misinterpret regular traffic signals designed to control transit vehicles as applying to them, leading to potential conflicts.

Applications

The MUTCD (Section 4D.27) identifies the following applications for transit signal faces for buses when engineering judgment indicates that using these signal faces in place of standard red/yellow/green signal faces would reduce road user confusion:

- Public transit buses in queue jump lanes, and
- Control of bus rapid transit in mixed traffic and bus lanes (FHWA 2009).

MUTCD Figure 8C-3 illustrates the various transit signal faces. According to the MUTCD, the go signal can be used in a flashing mode to indicate "prepare to stop" when two faces are used, or a triangle symbol can be used when three faces are used. A diagonal bar indication can be used to indicate that a turn should be made (FHWA 2009).

In general, transit signal faces are potentially applicable in situations where transit vehicles are allowed to move at different times than parallel traffic.

Companion Strategies

Transit signal faces are used to support other strategies that involve giving buses a head start on other traffic or moving from potentially unexpected locations. These strategies include bus-only signal phases (Section 6.9), queue jumps (Section 6.10), pre-signals (Section 6.11), traffic signals installed specifically for buses (Section 6.12), queue bypasses (Section 8.6), median bus lanes (Section 8.7), contraflow bus lanes (Section 8.8), and reversible bus lanes (Section 8.9).

Constraints

State traffic laws and the state supplement to the MUTCD may not allow the use of transit signal faces, may not allow the use of particular faces (e.g., triangles), or may require additional elements not specified in the national MUTCD, such as "Bus Signal" signs.

Benefits

Transit signal faces can reduce the potential for crashes that can occur when motorists or other road users misinterpret a standard signal display meant only for buses as being a green indication for them.

Cost Considerations

- **Planning and coordination costs.** Low to moderate. The first implementation in a jurisdiction will likely require a higher level of coordination with the roadway agency responsible for traffic signals, particularly if a signal controller upgrade is needed to support the bus signal phase and signal faces. Outreach to the police (about the meaning of the signals) and the public (that buses may move in advance of other traffic) is also suggested the first time transit signal faces are used in a jurisdiction. Subsequent implementations will likely require coordination only with the roadway agency.
- **Capital costs.** Moderate, but in a fairly large range covering signal heads and wiring only to a signal controller upgrade.
- **Maintenance costs.** Low additional cost to maintain the extra signal equipment.
- **Bus operations costs.** No direct impact but helps support other strategies designed to provide benefits. To the extent that they reduce road user confusion, the signals may provide a safety benefit relative to using shielded standard signal heads.
- **Other user costs.** No direct impact, but used in conjunction with other strategies, may produce other user costs or benefits.

Implementation Examples

Transit signal faces have been implemented in conjunction with a number of BRT projects employing median bus lanes, such as in Cleveland, Ohio; Eugene, Oregon; and Orlando, Florida; and for a number of bus-only signal phase and queue jump applications, such as in Calgary, Alberta; Las Vegas, Nevada; and San Francisco, California.

Implementation Guidance

Assuming that state and local laws, rules, and policies permit their use, transit signal faces are suggested for consideration in conjunction with any of the strategies listed in the Companion Strategies section.

Additional Resources

- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—Section 4D.27 addresses the use of light rail transit (LRT) signals for bus transit; Section 8C.11 describes LRT signals, their operation, and their installation requirements.

6.9 Bus-Only Signal Phases

Description

A traffic signal phase included in the traffic signal cycle to serve bus movements that cannot be served, or are not desired to be served, concurrently with other traffic.

Purpose

Bus-only signal phases help support other strategies, such as queue jumps (Section 6.10) and bus lanes (Section 8.1), by allowing buses to make nonstandard movements at an intersection. Without such signals, some transit-supportive roadway strategies might not be feasible (e.g., queue jumps), while others would be less effective (e.g., ending a bus lane a block or two early to give buses time to move across traffic lanes to a standard left-turn lane).

Applications

One typical application allows a bus turning movement from a nonstandard location, such as making a left turn from a right-side bus lane, making a right turn from a left-side bus lane, or movements to and from a median bus lane. Another typical application is to give buses a head start on parallel traffic, such as with a queue jump (Section 6.10). Figure 4 illustrates the

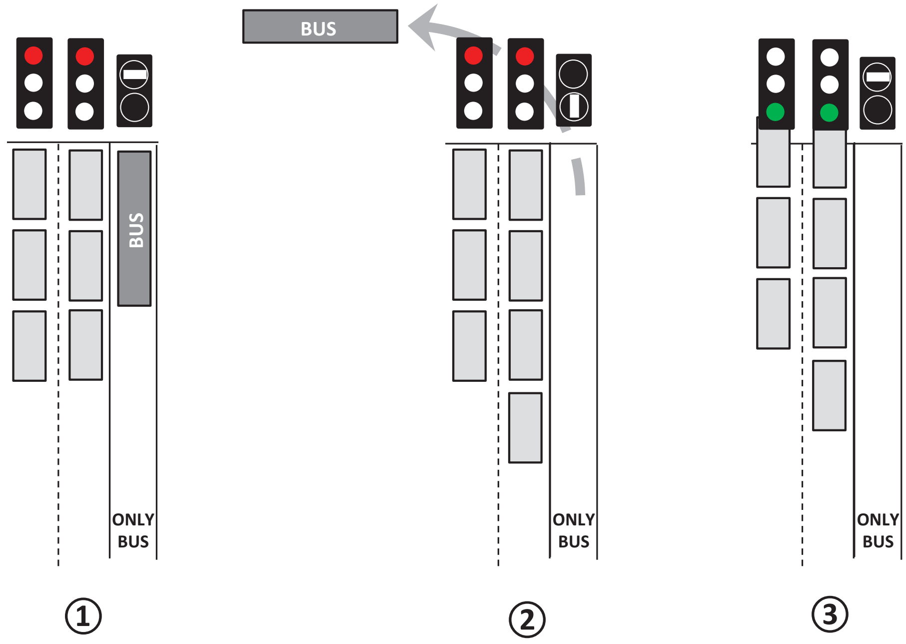


Figure 4. Example of bus-only signal phase operation.

operation of a bus-only signal phase used to allow buses to make a left turn from a right-side bus lane.

Companion Strategies

The need for transit signal faces (Section 6.8) should be considered when implementing bus-only signal phases. These phases can be used in conjunction with movement restriction exemptions (Section 6.1), TSP (for example, to call the special bus phase sooner) (Section 6.7), queue jumps (Section 6.10), pre-signals (Section 6.11), bus-specific signals (Section 6.12), queue bypasses (Section 8.6), median bus lanes (Section 8.7), contraflow bus lanes (Section 8.8), and single-lane reversible bus lanes (Section 8.9).

Constraints

State or local laws may not allow bus turns from nonstandard locations or allow the use of transit signal faces (Section 6.8). The signal controller needs to have an unused phase available to serve the bus-only phase. Bus turning radii will need to be checked, particularly for a right turn from a left-side lane, and it may be necessary to set the stop bar for the general traffic lanes back from the intersection to create sufficient space for a bus to make its turn. As the time required to serve the bus phase will be taken from other traffic movements, traffic operations will need to be evaluated to make sure that the signal will still operate acceptably with the addition of the extra phase.

See the Implementation Guidance section for potential alternatives when one of these constraints makes a bus-only signal phase infeasible.

Benefits

Bus-only signal phases are typically a support strategy and make another strategy feasible or allow another strategy to be used to maximum effectiveness. When used to serve turning movements from unconventional locations, they may reduce travel time or travel time variability, depending on the level of traffic congestion and challenges faced by buses to weave through traffic to position themselves to make a turn from a conventional location. The potential benefit is highly site-specific and would need to be determined by a traffic analysis.

Cost Considerations

The cost considerations associated with transit signal faces (Section 6.8) may also be applicable.

- **Planning and coordination costs.** Low to moderate. The first implementation in a jurisdiction will likely require a higher level of coordination with the roadway agency responsible for traffic signals, particularly if a signal controller upgrade is needed to support the bus signal phase and signal heads. Public outreach may also be needed to minimize the risk of increased crashes resulting from other roadway users reacting incorrectly to the new signal operation, particularly during the first year of operation.
- **Capital costs.** None to moderate, depending on whether bus detection infrastructure exists or would be installed for another strategy and whether a signal controller upgrade is needed. Accessible pedestrian signals may also be required.
- **Maintenance costs.** No direct impact.
- **Bus operations costs.** When used to serve unconventional turning movements, the strategy may reduce delays associated with buses weaving across traffic lanes to a location where a conventional turning movement can be made.
- **Other user costs.** The time required to serve a bus-only signal phase will likely increase delay for at least some other vehicles using the intersection.

Implementation Examples

- **San Francisco, California.** A bus-only signal phase was used to allow buses to make a right turn from a left-side bus lane on a one-way street. The combination of the three-block bus lane and bus-only signal phase saved buses 1.5 min of travel time compared to waiting in traffic to make a conventional right turn and also reduced travel time variability, as measured by the standard deviation of travel times, by more than half (Mirabdal and Thesen 2002). After the closure of the old Transbay Terminal, the bus line was rerouted and the bus-only signal phase taken out of service since buses no longer turned at that location. At the time of writing, the strategy was being considered at other locations on a case-by-case basis.
- **Eugene, Oregon.** A bus-only signal phase was used to allow buses to make a right turn from a left-side reversible bus lane on a one-way street. After the route realignment, the bus-only phase supports a queue jump operation, providing buses with a head start on other traffic so they can merge across the street to enter a right-side bus lane that begins one block downstream.
- **Richmond, British Columbia, Canada.** A bus-only signal phase was used to provide priority for many buses exiting the former Airport Transit Centre. The phase served both left-turning buses (toward Vancouver International Airport) and through bus movements (toward downtown Vancouver). After the Canada Line rail extension opened to the airport, the transit center was closed and the bus-only signal phase taken out of service.

Implementation Guidance

Special bus phases are a potential option when bus turning movements need to be made from unconventional locations. Designs may need to take into consideration conditions where other intersection users need to be warned about the unconventional movement (e.g., "Bus Signal" signs, accessible pedestrian signals, a special sign depicting the bus maneuver, dotted pavement markings), and the conditions listed in the Constraints section will need to be checked and potentially addressed prior to proceeding.

Use with Median Bus Lanes

If buses must leave a median bus lane at a signalized intersection, a special bus phase will be needed to serve them. When not all buses will turn and bus volumes are relatively high, it may be desirable to provide a separate bus turn lane. A turn lane allows both a through bus phase and a right- or left-turn bus phase to be provided. Late-arriving turning buses wait in the turn lane until the next cycle, while through buses can continue to be served at the same time as parallel general traffic through movements. In this way, turning buses do not delay through buses, and the length of the special bus phase can be minimized, reducing its impact on other traffic. However, constrained median widths may make it impractical to provide turn lanes, particularly at intersections where busway stations will also be located.

An alternative to a special bus phase, particularly when turning bus volumes are low, is to start the median bus lane's bus phase at an upstream intersection before parallel traffic receives a green signal, thus giving buses a gap in traffic that allows them to move out of the bus lane and into the correct general traffic lane for their turn at the downstream intersection. Another alternative is to provide a midblock "slip-ramp" exit from the median bus lane that allows buses to merge into general traffic (AASHTO 2014).

Use with Right-Side Bus Lanes

In most cases, a pre-signal or an upstream queue jump can provide the necessary gap in traffic that would allow buses to merge across lanes to use a standard left-turn lane to make their turn. However, there may be times (e.g., a high-volume passenger generator best served by a near-side bus stop, an over-capacity left-turn movement) where it would be desirable to allow buses to make a left turn from a right-side bus lane. In these cases, a special bus phase could be considered.

Use with Left-Side Bus Lanes

Similar to right-side bus lanes, a pre-signal or upstream queue jump can often address the need to move buses from one side of the street to the other to prepare to make a turn. However, there may be times (e.g., a high-volume passenger generator on the left side of a one-way street, traffic congestion in the block preceding the right turn) when it would be desirable to allow buses to make a right turn from a left-side bus lane. In these cases, a special bus phase could be considered.

Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.5.5.2 discusses the potential need for a special bus phase (possibly in conjunction with a separate bus right-turn lane) when a high volume of buses make right turns from a left-side bus lane. Section 5.6.2.2 discusses the potential need for a special bus phase in conjunction with median bus lane operations.

6.10 Queue Jumps

Description

Buses (or in some applications, buses and right-turning vehicles) are given an opportunity to move ahead of queued through-vehicles at a signalized intersection and, in many cases, to proceed into the intersection in advance of the through traffic.

Purpose

Queue jumps are a combination infrastructure and traffic control strategy. First, buses are provided the opportunity to bypass any queue of vehicles that might exist at a traffic signal. Second, a special signal phase allows the buses to depart the intersection ahead of other through-vehicles and, thus, jump the queue. If a near-side bus stop exists at the intersection, and if buses are ready to proceed at the start of the green, buses arriving on red do not have to wait for the queue in front of them to clear to access the bus stop, and they do not have to wait for a gap in traffic when departing the stop. If a far-side bus stop or no bus stop exists at the intersection, buses arriving on red bypass the queue and get through the intersection sooner than they would have otherwise.

Applications

Figure 5 illustrates three typical ways that a queue jump can be developed. The Implementation Guidance section provides more specific design and implementation guidance.

- **Shared right-turn lane.** A right-turn lane is provided that is longer than the queue length in the through lanes, allowing buses and right-turning vehicles free access to the lane (Figure 5a). Right-turning vehicles stopped in front of the bus can block the bus's access to a near-side bus

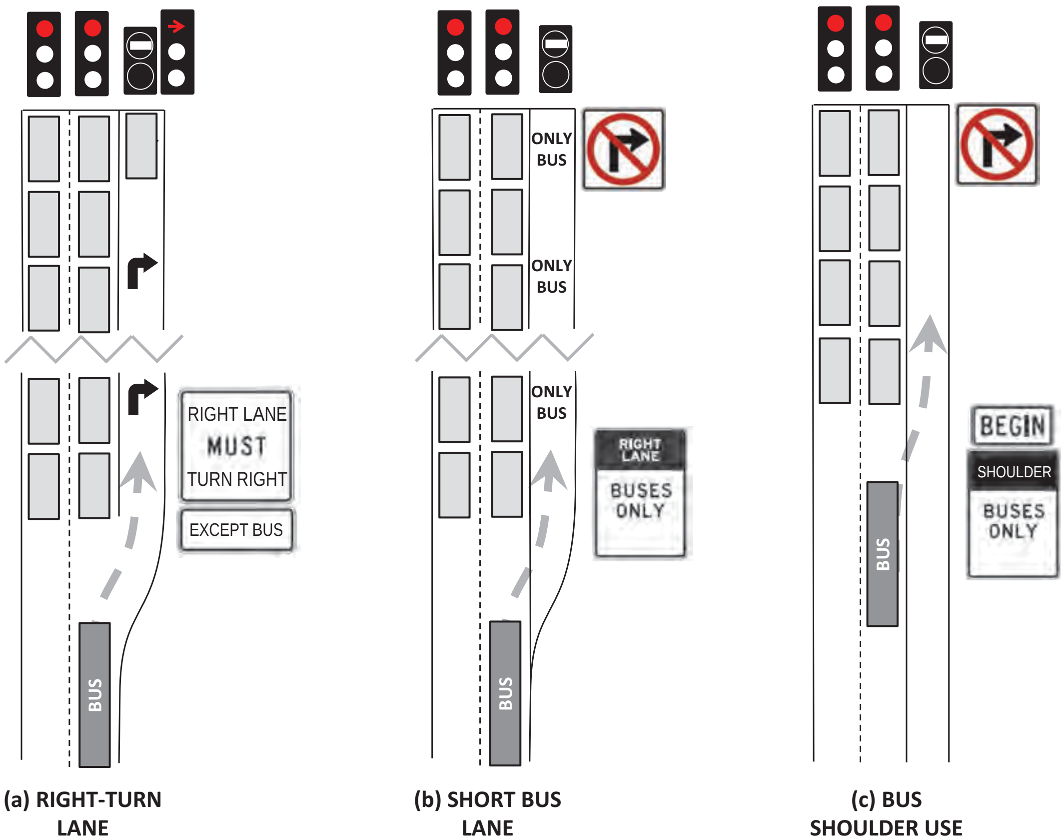


Figure 5. Illustrative examples of queue jump approaches.

stop; therefore, to avoid the potential for buses stopping twice (and needing to wait an extra cycle length), bus stops should be either located at the far side or prior to the start of the right-turn lane. If right-turning volumes are high, providing a separate right-turn lane and placing the bus stop on a right-turn channelization island (Section 7.6) may be a better option.

- **Short bus lane.** A short bus lane is provided that is longer than the queue length in the through lanes, allowing buses free access to the lane (Figure 5b). As right turns from the lane to the left of a bus lane are not recommended due to possible conflicts between right-turning vehicles and buses using the queue jump (AASHTO 2014), this option is best suited for intersections without right-turn movements. These include T-intersections where the minor street approaches from the left, intersections with one-way streets approaching from the right, and intersections with low right-turn volumes that can be shifted to an upstream or downstream intersection. The bus stop can be located at the near side at the stop bar or one bus length prior to the stop bar (depending on how buses will be detected to activate the queue jump phase), or can be located at the far side.
- **Shoulder bus lane.** This type of queue jump lane is operationally similar to a short bus lane, except that buses are allowed to use the shoulder when approaching the intersection (Figure 5c). The shoulder needs to have been constructed to support regular bus use. This type of lane is potentially applicable on suburban arterial streets and highways that use a shoulder instead of a curb and gutter on the edge of the roadway.

Figure 6 illustrates one potential way a queue jump in a right-turn lane can operate, assuming that the pedestrian push button has been pressed on the parallel crosswalk. In step 1, the bus is detected at the bus stop and the queue jump phase is called. In step 2, the queue jump phase is activated. A green arrow is provided for the right-turn lane, allowing any right-turning vehicles

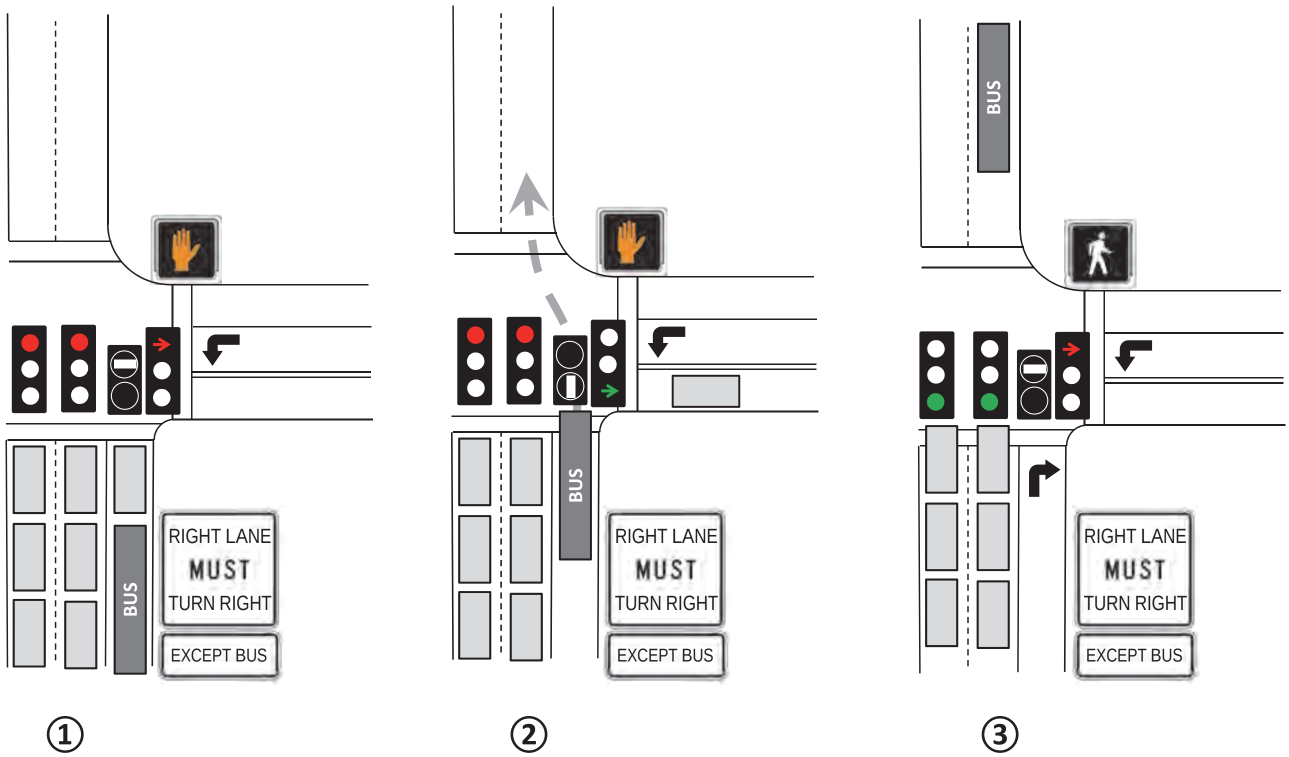


Figure 6. Illustrative example of queue jump operation from a right-turn lane with a near-side stop.

in front of the bus to clear out of the way so the bus can proceed into the intersection. In step 3, the bus has cleared the intersection, and parallel traffic and the parallel crosswalk phases are served. If no pedestrians need to be served on the crosswalk, the right-turn phase can continue as long as the through green phase is served. If a bicycle lane is provided on the roadway, it would be located to the left of the right-turn lane and served at the same time as the parallel through traffic. Other options for accommodating right-turning traffic are discussed in the Implementation Guidance section.

When short bus lanes and shoulder lane queue jumps are employed, parallel pedestrians and bicycles can be allowed to start moving at the same time as buses since there are no other conflicting movements when right turns are prohibited. If no bus stops are provided at the intersection, bus drivers can decide whether to use a queue jump lane, depending on whether they arrive at the intersection on a green or red signal.

Figure 7 illustrates a queue jump from a short bus lane into a far-side bus pullout. In this case, it is not necessary to provide an advance green to buses because they stay in their own lane and thus do not conflict with the parallel through traffic, and right turns are prohibited. The short bus lane prior to the traffic signal provides the time savings for the bus by allowing it to bypass the queue waiting at the signal.

The parallel pedestrian movement is served at the same time as buses and general traffic. See Appendix C for concepts for accommodating bicycles in the vicinity of the bus stop.

Companion Strategies

Queue jumps can be used in combination with bus stop relocations (Section 5.1), movement restriction exemptions (Section 6.1), right-turn restrictions (Section 6.2), phase reservice

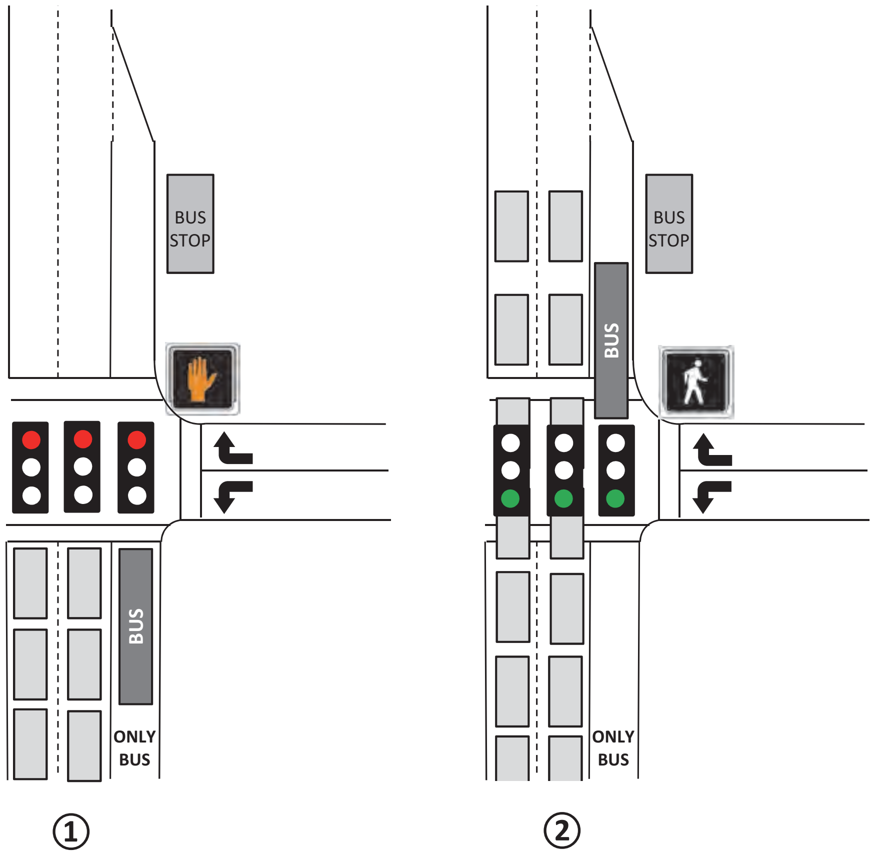


Figure 7. Illustrative queue jump operation from a short bus lane with a far-side stop.

(Section 6.5), and transit signal priority (Section 6.7). A bus-only signal phase (Section 6.9) is often employed as part of the queue jump and may be indicated using transit signal faces (Section 6.8). Red pavement coloring (Section 7.4) is a potential support strategy for short bus lanes. Pre-signals (Section 6.11) and queue bypasses (Section 8.6) are related strategies.

Constraints

A constraint common to any queue jump configuration is the need for a sufficiently long lane to allow buses unimpeded access to the lane under most circumstances. AASHTO (2011) recommends that 1.5 to 2 times the average peak-period queue length be used in designing turn lane storage lengths, which approximate 85th- and 95th-percentile queues, respectively. However, simulation studies by Cesme et al. (2015) found that bus delay was relatively insensitive to the queue jump lane length when buses arrived randomly, with designs accommodating a 35th-percentile queue resulting in only a 1.3-s reduction in the delay benefit at a *v*/*c* ratio of 0.9 relative to a 95th-percentile queue design; smaller delay reductions were observed at lower *v*/*c* ratios.

Nevertheless, the lack of available right-of-way or the cost of extending or constructing a queue jump lane may constrain a transportation agency's ability to implement a queue jump. A traffic analysis can determine queue length percentiles (both current and future design year conditions should be considered) as an input for determining the required lane length, and can also determine the probability that an arriving bus would not be able to access the queue jump lane.

Another potential constraint is the ability to provide sufficient time during the traffic signal cycle to the queue jump, particularly in the case of shared right-turn lanes. The potential benefit of queue jumps grows as traffic volumes increase, but the ability to reallocate time within the signal cycle diminishes. The *Highway Capacity Manual* (HCM) or analytical techniques can be used to determine how much time on average would be required to serve the queue jump lane and, subsequently, how the intersection would operate with the revised signal timing. If right-turning volumes are too high to be served with a protected phase, they would need to be served as a permitted movement from their own lane to the right of a bus lane, which again raises the question of available right-of-way and the potential need to reconstruct curbs and sidewalks to add the extra width. In these cases, it is not necessary to widen the full length of the queue jump lane, just the portion closest to the intersection (see Section 7.6 on boarding islands).

Traffic laws may need to be revised to allow buses to continue straight from a right-turn lane.

Benefits

When through-traffic queues are long (due to high traffic volumes or long traffic signal cycle lengths) and right-turning traffic is low or non-existent, the queue bypass aspect of queue jumps can potentially save buses significant amounts of time. As a rule of thumb, the time savings is equivalent to 2.25 s times the number of vehicles queued in the right-hand through lane when the bus arrives at the intersection minus 2.5 s times the number of vehicles queued in the queue jump lane when the bus arrives. However, if the bus arrives on green and proceeds to a far-side stop, no time savings result. Therefore, the actual delay benefit depends on when in the traffic signal cycle buses and other traffic arrive at the intersection. The advanced-green aspect of queue jumps saves buses no additional time since the time is typically taken from the parallel through traffic. Instead, the through traffic experiences extra delay because the traffic signal serves them later than they would have been served otherwise.

A simulation analysis conducted under TCRP Project A-39 found that, for a queue jump designed for 95th-percentile queues, the tested queue jumps produced no significant change in bus travel times at v/c ratios of 0.5 for both near- and far-side stops and a v/c ratio of 0.8 for far-side stops. For near-side stops, buses experienced average delay reductions of 1.5 and 7 s for v/c ratios of 0.8 and 1.0, respectively, while parallel through traffic experienced average delay increases of 1 and 2 s per vehicle, respectively. For far-side stops, bus delay was reduced an average of 2 s at a v/c ratio of 1.0, while parallel through traffic experienced average delay increases of 3 s per vehicle. A simulation study by Cesme et al. (2015) found reductions in average bus delays of between 2 and 9 s for v/c ratios ranging from approximately 0.5 to 0.9 for a queue jump designed for 95th-percentile queues and no right turns allowed.

If the queue jump is developed by restricting right turns so that they occur only during a protected right-turn phase, pedestrians benefit from the reduced number of interactions with right-turning traffic (i.e., none from the queue jump lane, but potentially right turns on red from the side street approach).

Cost Considerations

The cost considerations associated with transit signal faces (Section 6.8) and bus-only signal phases (Section 6.9) may also be applicable.

- **Planning and coordination costs.** Low to moderate. An analysis of the effect of the queue jump on intersection operations and users is recommended. The first implementation in a jurisdiction will likely require a higher level of coordination with the roadway agency. Outreach to the police (about any special traffic regulations such as bus use of the right-turn lane) and the public (about queue jump operation generally) is suggested the first time a queue jump is implemented in a jurisdiction. Subsequent implementations will likely require coordination only with the roadway agency.

- **Capital costs.** Moderate to high. Sign costs are low, but construction and potential right-of-way acquisition costs to construct or lengthen the queue jump lane are potentially high. There are also signal-related costs previously discussed as part of related strategies. Accessible pedestrian signals may be required.
- **Maintenance costs.** Potential low to moderate added cost to maintain extra signs, extra pavement area, and detection equipment.
- **Bus operations costs.** Relatively small time savings benefits, except when the intersection operates close to capacity.
- **Other user costs.** Small increase in average delay to parallel through traffic if time is taken from its phase to provide an advanced green for buses. More substantial potential increase in delay to right-turning traffic if right turns are restricted to a protected right-turn phase only or if right turns are relocated to another intersection.

Implementation Examples

A survey of 52 North American transit agencies found that 27 reported having installed at least one queue jump or queue bypass lane. Of these, Ottawa, Ontario (8), Halifax, Nova Scotia (8), and King County Metro (Seattle, Washington [6]) were notable for the number of installations (Danaher 2010). A shoulder lane queue jump exists on southbound U.S. 202 near Wilmington, Delaware (Martin et al. 2012).

Implementation Guidance

General Guidance

The following characteristics make a signalized intersection more suitable for a queue jump:

- Near-side stop is desired for non-operational purposes (e.g., to facilitate passenger transfers, to serve near-side land uses), or no bus stop is provided at the intersection;
- Ending point of a bus lane, existing shoulder suitable for buses, or existing right-turn lane;
- No or low (e.g., a few vehicles per cycle) right-turning traffic;
- Low pedestrian usage of the parallel crosswalk (if one exists); and
- High peak-period intersection *v*/*c* ratio (e.g., 0.7 or greater), but sufficiently below capacity that green time can be taken to serve the queue jump phase.

Bus Stop Location

Not having a bus stop at the intersection provides the most flexibility in selecting a specific queue jump application and is compatible with any of the queue jump applications depicted in Figure 5.

Near-side stops work best in conjunction with short bus lanes or shoulder lanes. They also can work in a shared right-turn lane application when the right turns are channelized and the bus stop can be placed on the channelizing island (see Section 7.6). When right turns have an exclusive lane but are not channelized, placing the bus stop at the stop bar is not recommended unless it is highly likely that buses can access the stop without stopping twice (for example, because of a queue jump at the upstream signal); otherwise, buses risk having to wait through another signal cycle before they can depart (and also block right-turning traffic behind them). Placing the bus stop elsewhere in the right-turn lane is also not recommended since it encourages right-turning traffic to cut in front of buses, leading to potential conflicts with both buses and bicycles. Placing a stop prior to the start of the right-turn lane is an option, but this may be inconveniently far from the intersection for passengers.

Far-side stops also work best in conjunction with short bus lanes or shoulder lanes and eliminate the requirement for a special queue jump phase since buses do not need to merge back into traffic immediately. Far-side stops can be used in conjunction with shared right-turn lanes but may not provide any operational benefit or may even provide a disbenefit. A simulation study found that a disbenefit resulted with the following combinations of right-turning vehicles and pedestrians in the parallel crosswalk:

- 100 or more right-turning vehicles per hour, with 300 or more pedestrians per hour;
- 200 or more right-turning vehicles per hour, with 150 or more pedestrians per hour; or
- 300 or more right-turning vehicles per hour, with nearly any pedestrian volume (Cesme et al. 2015).

Queue Jump Lane Length

The desirable queue jump lane length is one that is at least as long as the 85th- or 95th-percentile peak-period queue in the through lane. However, shorter lengths may function adequately, and accepting a shorter lane length may be a more cost-effective solution than providing the desirable length. A simulation study found that the bus delay benefit was reduced by no more than 1.3 s when a 35th-percentile length was used, compared to a 95th-percentile length when buses arrived randomly (Cesme et al. 2015).

Conditions at the upstream stop will help determine when a bus is likely to arrive at the intersection relative to other through traffic. If buses are likely to arrive ahead of other traffic (e.g., due to an upstream queue jump) or randomly, shorter queue jump lane lengths will likely operate satisfactorily. If buses are likely to arrive behind other traffic (e.g., due to an upstream bus pullout), queue jump lane lengths closer to the desirable length will likely be necessary.

Options for Serving Right-Turning Traffic

If right-turning traffic cannot be diverted to another intersection, then short bus lanes and shoulder lanes are not options since it is undesirable to have traffic turn right from the lane to the left of the queue jump lane (AASHTO 2014). Options for serving right-turning traffic, in order of desirability, are:

- **Separate, channelized right-turn lane.** The bus stop (if any) is placed on a channelizing island and is served by a short bus lane accessed from the right-turn lane (see Section 7.6). The time required for the queue jump phase is minimized since only buses need to be served. Pedestrians have to cross to the channelizing island to reach the main intersection crosswalks, which is less convenient and potentially more time-consuming for them compared to not having a channelizing island. Right turns can begin to be served when the queue jump phase is served.
- **Protected (i.e., green arrow) right-turn phase with the queue jump phase.** Right-turning vehicles and buses are served first (if buses need to use the intersection to merge back into the through lane) or start simultaneously with through traffic (if buses continue to a far-side stop). If a pedestrian call needs to be served on the parallel crosswalk, right turns are stopped at the end of the queue jump phase and the crosswalk is served while parallel through traffic continues to be served. If no pedestrian call is waiting, right turns continue to be served through the end of the parallel through-traffic phase. Pedestrians benefit from the absence of conflicting right-turning traffic (although right turns on red may still occur at the opposite end of the crosswalk). This option requires the longest queue jump phase length in order to accommodate the potential of the bus being at the back of the right-turn queue; therefore, it may not be feasible with more than a few right-turning vehicles per cycle.
- **Permitted (i.e., circular green) right-turn phase.** This is an option with far-side stops, but if even moderate right-turn volumes exist, it can result in greater bus delay than simply allowing

the bus to use the through lane to access the far-side bus stop. It can also be used with near-side stops if one is willing to accept that the bus will often stop twice when accessing the stop. In the latter case, a short queue jump phase can be provided after the parallel through traffic phase ends for use if the bus is ready to depart.

- **Protected/permitted right-turn phase with a queue jump phase.** This option first provides a protected right-turn/queue jump phase to clear out any right-turning vehicles in front of the bus. At the end of the queue jump phase, the parallel through traffic and parallel crosswalk phases begin. Right turns can still be made during this time, but vehicles must yield to pedestrians in the crosswalk. This option reduces vehicular right-turn delay relative to a protected-only option but is least desirable from a pedestrian standpoint since the pedestrian phase starts after right-turning traffic. This situation can lead to late-arriving, right-turning motorists not realizing there are now pedestrians in the crosswalk; the potential conflict is similar to that experienced with protected/permitted left turns. Additional signs, such as "Turning Vehicles Yield to Pedestrians" (MUTCD sign R10-15) may be necessary if this option is used.

Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.3.2.3 provides AASHTO's recommendations for queue jumps (note that AASHTO's usage of the terms *queue jump* and *queue bypass* are the opposite of this guidebook and other TCRP publications).

6.11 Pre-Signals

Description

A traffic signal for one direction of a street, coordinated with a traffic signal at a downstream intersection, that is used to control the times when particular vehicles may approach the intersection.

Purpose

In a transit context, pre-signals are used at the end of a bus lane to give buses priority access to the intersection when constraints make it infeasible to continue the bus lane all the way to the intersection. They can also be used to manage queues on the intersection approach—for example, when a side street or driveway is regularly blocked by queues extending back from the traffic signal.

Applications

A significant challenge when implementing bus lanes is the loss of vehicular capacity that results at signalized intersections if a general-purpose lane is converted to bus-only use. Because traffic signals meter the amount of traffic that can pass through an intersection, it is often possible for a roadway to have sufficient capacity between traffic signals to convert a lane to bus-only (or bus-plus-right-turn) use but not have sufficient capacity to provide a bus lane at the traffic signal. Pre-signals address this issue by moving buses to the head of the line at traffic signals (thus minimizing bus delay) while maximizing the amount of roadway space that can be used for general traffic movement at the intersection (thus using the intersection as efficiently as possible). When the pre-signal is properly located and timed relative to the main intersection signal, the transit benefit can be achieved with no loss of intersection capacity and negligible delay to general traffic.

There are three main applications of pre-signals:

- **Virtual bus lane.** In this application (Figure 8), queues on a congested approach to a traffic signal extend well back from the signal, and it may take several traffic signal cycles before a vehicle can get through the intersection once it joins the back of the queue. A pre-signal is used both to manage queues at the intersection—metering only as much traffic to the intersection as can be served in the approach's green interval—and to provide a virtual bus lane between the pre-signal and intersection that is clear of other traffic at the time the bus needs to use it. In this application, the pre-signal serves as a signalized queue bypass.
- **Merge assist.** In this application, the right-of-way used by the bus lane is needed for other purposes downstream—for example, for a right-turn lane at the downstream intersection or for curbside parking. A traffic signal assists buses in merging into the adjacent general traffic lane in front of other traffic. This application can also be used to assist buses in reentering traffic from an offline bus stop (e.g., a bus pullout), such as in the photograph at the beginning of this section.

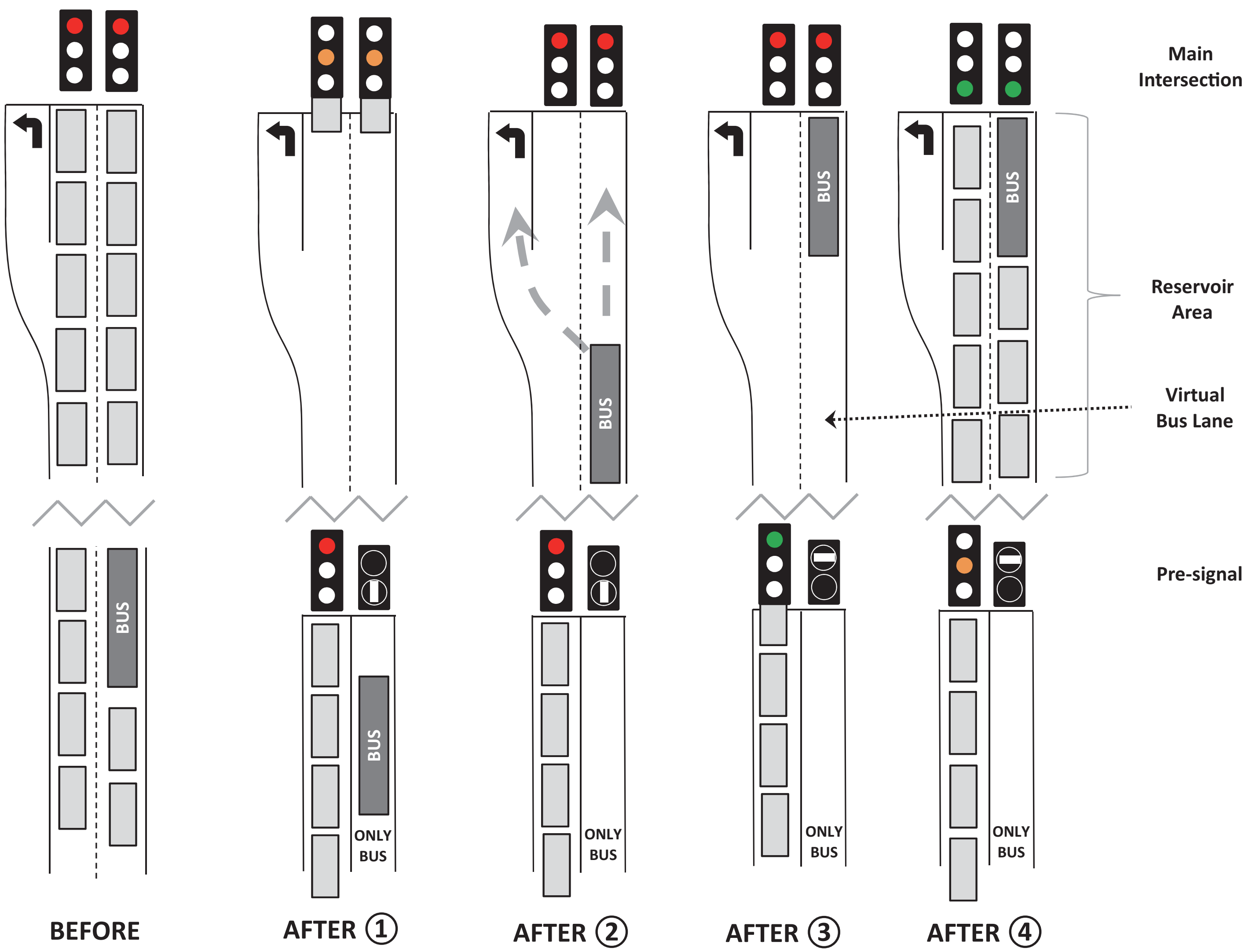


Figure 8. Examples of virtual bus lane and weave-assist applications for pre-signals.

- **Weave assist.** In this application, buses need to exit a bus lane to turn left at a downstream intersection. The pre-signal provides a gap in traffic that allows buses to weave from a right-side bus lane to the left-turn lane.

Figure 8 illustrates one possible configuration for a pre-signal. In the before case, the approach lanes to the intersection operate over capacity, and buses experience the same delay as other vehicles. In the after case, the right lane is converted to a bus-only lane, while the left lane(s) are used by general traffic. One more general-purpose lane is provided after the pre-signal than before the pre-signal, using the space that had been occupied by the physical bus lane, thus maximizing vehicle throughput at the intersection. The pre-signal is preferably installed on the approach at a location that ensures that all of the vehicles that pass the pre-signal can be served on the next green at the intersection. The back of the queue extends farther back than previously, but the same number of vehicles pass through the signal each cycle and a bus lane allows buses to bypass the queue.

In step 1 of the after case, the pre-signal for general traffic has turned red, and the final vehicles that passed the pre-signal are entering the intersection as its signal turns yellow. At the end of this step, the reservoir area between the pre-signal and the intersection is clear of vehicles. Next, in step 2, the pre-signal for bus traffic changes to "go," allowing buses to bypass the queue and proceed to the intersection stop bar (or left-turn lane) unimpeded. In step 3, the bus pre-signal changes to "stop," the general traffic pre-signal changes to green, and general traffic is allowed to fill the reservoir area between the pre-signal and the intersection. Finally, in step 4, the intersection traffic signal turns green, allowing the queued traffic to proceed, while at the same time the pre-signal stops additional vehicles from entering the reservoir area.

Companion Strategies

A bus lane (Chapter 8) is a prerequisite for employing a pre-signal. It is suggested that the bus lane be controlled by transit signal faces (Section 6.8) providing a bus-only signal phase (Section 6.9). Transit signal priority (Section 6.7) can potentially be applied both at the pre-signal and the downstream signal.

Queue jumps (Section 6.10), where priority is provided at the signalized intersection, and queue bypasses (Section 8.6), which do not use traffic signals, are related strategies.

Constraints

Pre-signals are a support strategy for bus lanes, and therefore the constraints generally applicable to bus lanes (Section 8.1) also apply to pre-signals. Properly implemented, they do not affect the signal timing or approach throughput at the downstream intersection; however, the presence of side streets or driveways may require locating the pre-signal at a less-optimal location that may affect intersection throughput. Their main impact lies in relocating the queue from the intersection to an area farther upstream from the intersection. When the pre-signal helps facilitate the conversion of a general-purpose lane to a bus lane, the queue in the remaining general-purpose lanes will become longer (up to twice as long).

Benefits

When an intersection operates over capacity, a pre-signal's ability to allow buses to bypass the queue can result in substantial time savings; the combination of a bus lane and pre-signal in York, United Kingdom, was reported to save buses 4 to 12 min per trip during peak periods

(Hodge et al. 2009). The magnitude of the potential time savings will depend on the severity of the congestion. When an intersection operates under capacity, the main benefit is facilitating bus movements into or across the general traffic lane(s). Pre-signals will also tend to reduce bus travel time variability.

Cost Considerations

- **Planning and coordination costs.** Moderate. A traffic analysis will be needed to identify the optimal location for the pre-signal. A signal timing plan will need to be developed for the pre-signal and coordinated with the downstream signal. Planning and coordination costs associated with transit signal faces (Section 6.8) and special bus phases (Section 6.9) will also be applicable. Outreach to the stakeholders normally interested in bus lane projects (Section 8.1) is also suggested.
- **Capital costs.** Moderate to high, involving obtaining and installing the traffic signal equipment for the pre-signal. Depending on how close the pre-signal is to the downstream signal, the signal faces for the approach at the downstream signal may need to be replaced with visibility-limited signal faces that are only visible once motorists pass the pre-signal.
- **Maintenance costs.** Moderate, involving added costs for operating and maintaining the pre-signal.
- **Bus operations costs.** Potential savings from reductions in travel time and travel time variability.
- **Other user costs.** Properly implemented, there will be no change in general traffic delay. However, the presence of driveways, unsignalized intersections, or other queue management concerns may require locating the pre-signal in a less-optimal location that does affect general traffic delay.

Implementation Examples

At the time of writing, no U.S. or Canadian installations were known to exist, but many installations have been documented elsewhere in the world. In particular, London has had considerable experience with pre-signals, with at least 21 signals in operation by mid-1998 (Beswick 1999). Other installations documented in the literature are Manchester and York, United Kingdom; Frederiksberg, Lyngby, and Svendborg, Denmark; Zurich, Switzerland; Melbourne and Brisbane, Australia; and Wellington, New Zealand.

Implementation Guidance

General Guidance

The presence of a bus lane or an extended bus pullout is a prerequisite for considering a pre-signal. The pre-signal should operate full time unless there are overriding reasons not to do so (Beswick 1999). To obtain maximum benefit for buses, locate bus stops either immediately prior to the pre-signal or on the far side of the intersection.

Virtual Bus Lane Applications

- Pre-signals providing a virtual bus lane are well-suited for the critical intersection(s) along a bus route where as many roadway lanes as possible are needed to serve through traffic. These are the intersections with the highest demand-to-capacity ratios.
- It is frequently not necessary to continue the bus lane past the critical intersection since the intersection limits the amount of traffic that can enter the next block, and bus operation in mixed traffic downstream of the critical intersection may operate without problems.

- If the bus lane is restarted downstream of the intersection, the right lane will operate as an auxiliary through lane and will likely not be fully utilized. Procedures in *NCHRP Report 707: Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections* (Nevers et al. 2011) can be used to estimate the amount of traffic that will use the right lane.

Merge-Assist Applications

Pre-signals providing a merge-assist function can be considered for locations where:

- Policy needs (e.g., providing on-street parking for a commercial node along a street), geometric constraints (e.g., narrowed right-of-way), or traffic operation needs (e.g., providing a right-turn lane at the next intersection) dictate ending a bus lane; or
- Buses have difficulty reentering traffic from a midblock stop.

Weave-Assist Applications

Pre-signals providing a weave-assist function can be considered for locations where buses need to exit a bus lane to turn left at a downstream intersection.

MUTCD Compatibility and Requirements

As part of the research behind the development of this guidebook, the research team corresponded with FHWA about the need for an experimentation request when applying pre-signals. The response from the FHWA staff person responsible for the MUTCD's traffic signals material was that no experimentation request would be necessary and that bus movements would preferably be controlled by transit (LRT) signal heads (see *TCRP Web-Only Document 66*).

The MUTCD already provides provisions for pre-signals in a railroad crossing context (FHWA 2009, Section 8C.09), for using priority control of traffic signals to assign priority right-of-way "to specified classes of vehicles at certain non-intersection locations," including transit operations (FHWA 2009, Section 4D.27), and for using transit signal heads to control public transit buses using "queue jumper lanes" (FHWA 2009, Section 4D.27). In addition, the use of pre-signals coordinated with a main intersection is similar to the use of supplemental signals with alternative intersection forms such as displaced left-turn intersections.

Pre-Signal Placement and Timing

For virtual bus lane applications, particularly when the main intersection operates at or near capacity, the pre-signal ideally would be located far enough away from the main intersection that all of the vehicles that can be served during the green interval during peak periods can be stored between the pre-signal and the intersection. Furthermore, during peak periods, the pre-signal ideally would be timed to turn green such that the entire area between the pre-signal and the intersection can fill with vehicles by the time the main signal turns green. During off-peak periods, when traffic volumes are lower and intersection efficiency is less important, the pre-signal could be timed to progress vehicles through to the main intersection without forcing traffic to stop twice.

Locating the pre-signal more than the ideal minimum distance from the main intersection is generally not an issue since there will simply be some empty space between the pre-signal and the back of the queue from the main signal. On the other hand, locating the pre-signal less than the ideal minimum distance from the intersection will result in lower intersection efficiency because the pre-signal will deliver fewer vehicles to the main intersection than can be served at the intersection toward the end of the approach's green interval.

With merge-assist applications, the number of general-purpose lanes at the pre-signal and the main intersection is the same, and therefore the pre-signal location is more flexible than in a virtual bus lane application. The pre-signal timing should allow vehicles to progress through to the main intersection without forcing traffic to stop twice.

In a weave-assist application, the number of general-purpose lanes downstream of the pre-signal may be greater than those upstream (e.g., if all buses will turn left and the bus lane is no longer needed), in which case the placement considerations are similar to a virtual bus lane application, particularly if the approach operates at or near capacity. Otherwise, if the bus lane continues past the pre-signal (e.g., some buses continue straight instead of turning left), the placement considerations are similar to those of a merge-assist application, with the additional consideration that buses will need sufficient roadway space to weave over to the left-turn lane.

Similar to other types of traffic signals, pre-signals should not be installed at an unsignalized intersection or within 100 ft of one. Consider the need for visibility-limited signal faces at the downstream intersection (FHWA 2009).

Queue Management Considerations

The location of the pre-signal and the expected back of the queue relative to upstream driveways and intersections requires special consideration. Access management measures (e.g., closing or consolidating access points) may be needed if queues from the pre-signal regularly block access points; in a worst case, access point blockage could pose a fatal flaw to installing pre-signals. The *Access Management Manual* (Williams et al. 2014) provides guidance on potential access management strategies, and bus lane and pre-signal installation could be considered in conjunction with an overall access management plan for a corridor. At the same time, pre-signals can provide an access management benefit when access points are located close to a traffic signal, cannot be readily moved or closed, and are frequently blocked by stopped traffic.

Pedestrian Considerations

If pedestrian volumes warrant a signalized pedestrian crossing, a pre-signal could be installed in conjunction with a midblock pedestrian crossing; this type of treatment has been documented internationally (e.g., Beswick 1999, Greater Manchester Public Transport Authority 2007). Although pedestrian jaywalking at pre-signals has not been identified as an issue in the international literature, evaluating the potential for jaywalking at a potential pre-signal site may result in possible countermeasures being identified, such as "No Pedestrian Crossing" signs, landscaping, or railings.

Bicycle Considerations

The same considerations described in Appendix C that generally apply to bicycle facilities shared with or adjacent to bus lanes also apply to pre-signals. In addition, if the bicycle facility type changes downstream of the pre-signal (e.g., from shared bus/bike to general-purpose lane), pavement markings may be required downstream of the pre-signal to direct bicyclists and to warn other road users about the presence of bicyclists. Unless the pre-signal is installed in combination with a signalized pedestrian crosswalk, it should not be necessary for bicycles traveling in their own lane to have to stop at the pre-signal. Options for addressing bicycle movements include (subject to local laws and policies):

- Where an exclusive bicycle facility is provided, a bicycle signal head could be provided (allowed by an FHWA Interim Approval, but still requires a formal request to FHWA until the MUTCD is updated); or
- Directing bicycles from the roadway onto a short section of cycle track or shared-use path that bypasses the signal. This is likely the only feasible option for shared bus/bike lane operation since bicycle signals cannot be used for shared-lane applications, bicycles in the shared lane should not be controlled by the vehicular signal (as buses would be blocked by stopped bicycles), and bicycles cannot be controlled by a transit signal. Although used in some European

countries, signs exempting bicycles from the traffic signal indications would be inconsistent with the meaning of traffic signal indications provided in the MUTCD.

Use with Transit Signal Priority

In many of the installations documented in the literature, pre-signals have been combined with forms of TSP at both the pre-signal and the intersection. In these installations, the pre-signal typically stops general traffic as soon as an approaching bus is detected (i.e., buses preempt the pre-signal), allowing the bus to proceed without stopping, while priority (red truncation or green extension, as appropriate) is employed at the downstream intersection. This approach has been shown internationally to have a net person-delay benefit (e.g., Koumara et al. 2007, Guler and Menendez 2013), but significant delays (e.g., 1 to 2 min) occur to motorists during the traffic signal cycles when buses arrive because the pre-signal delivers traffic to the intersection less efficiently in this form of operation.

This guidebook's suggestion is to not use priority or preemption at either the pre-signal or main intersection during times when the approach operates over capacity, due to their impact on intersection operations. Preemption of the pre-signal (if not also a pedestrian crossing signal), priority at the pre-signal, priority at the main intersection, or a combination of these, can be considered at other times, but it should be recognized that changing the timing of the pre-signal may make the downstream signal operate less efficiently.

Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.5.7.5 describes the weave-assist application of pre-signals, described as an "advance stop bar for bus left turns."
- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—Section 4D.27 addresses priority control of traffic signals for bus transit, and Section 8C.09 discusses pre-signals in a railroad crossing context.
- *TCRP Web-Only Document 66: Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies*—Appendix A presents the results of an international literature review on pre-signals.

6.12 Traffic Signal Installed Specifically for Buses

Description

An intersection that is signalized primarily to serve bus movements rather than general traffic.

Purpose

Buses may experience significant delays making turns at an unsignalized intersection along a major roadway, but the minor-street traffic volumes may not be sufficient to meet the MUTCD's volume-based traffic signal warrants.

Applications

Typical locations where a traffic signal specifically for buses might be considered are (1) unsignalized intersections where buses turn left onto or from a busy major street, (2) transit center and park-and-ride entrances or exits, and (3) off-street busway crossings of public roadways.

At the time of writing, the MUTCD did not provide a traffic signal warrant specifically for bus operations. However, some of the MUTCD's signal warrants not related to traffic volumes may be applicable to the intersection and could potentially be used to justify a traffic signal that would also benefit bus operations. These warrants are:

- **Warrant 4, Pedestrian Volumes.** A traffic signal may be warranted with pedestrian volumes crossing the major street of as low as 107 pedestrians per hour in each of 4 h of the day (depending on major-street traffic volumes), or as low as 75 pedestrians per hour when the major street posted or 85th-percentile speed exceeds 35 mph or the city population is under 10,000. A signal may also be warranted with peak-hour pedestrian crossing volumes of as low as 133 or 103 pedestrians per hour (depending on the major street speed and city population).
- **Warrant 6, Coordinated Signal System.** A traffic signal may be warranted if the nearest traffic signals are at least 1,000 ft away and an engineering study determines that traffic platooning on the major street will be improved with the installation of a signal.
- **Warrant 7, Crash Experience.** A traffic signal may be warranted if (1) the intersection has experienced at least five crashes within the last 12 months of types that could be corrected by traffic signal control, (2) other alternatives have failed to reduce the incidence of crashes, and (3) the 8-h traffic volume or the pedestrian volume warrant is met at a reduced level (FHWA 2009).

At the time of writing, the National Committee on Uniform Traffic Control Devices had approved text for a proposed new MUTCD chapter on busway grade crossings for FHWA's consideration for the next edition of the MUTCD. If adopted as written, bus-specific signals would be permitted "at busway grade crossings and at intersections where buses operate in mixed traffic in conjunction with standard traffic control signals where special bus signal phases are used to accommodate turning bus vehicles or where additional bus clearance time is desirable" (NCUTCD 2014a). However, until such time that language allowing signals specifically for buses is included in the MUTCD, roadway jurisdictions would need to submit an experimentation request to FHWA (see Appendix D) and have it approved to be able to use such signals.

Some Canadian provinces allow the use of a transit signal for transit purposes. Some Canadian jurisdictions permit the use of half signals that serve both pedestrian crossing and transit needs (Corby et al. 2013); however, half signals are not allowed by the MUTCD.

Companion Strategies

Traffic signals specifically for buses could be implemented using transit signal faces (Section 6.8) to control bus movements and would typically be used in conjunction with bus-only signal phases (Section 6.9). Transit signal priority (Section 6.7) could also potentially be provided. Traffic signal shadowing (Section 6.6) may be an alternative strategy if a signal specifically for buses is not feasible.

Constraints

One key potential constraint is regulatory—the ability to justify the traffic signal on the basis of an existing MUTCD warrant or by receiving an experimentation request. Some roadway jurisdictions only consider specific MUTCD warrants as a matter of policy and might need to change their policies to allow use of warrants not based on traffic volumes.

Another potential constraint is the effect of a new traffic signal on roadway operations. If the major street currently provides good traffic progression and the installation of a new signal would disrupt that progression, the roadway agency is unlikely to be in favor of a signal at the proposed location. If the signal is primarily for the benefit of the transit agency, the roadway agency may seek to have the transit agency bear the cost of operating and maintaining the signal.

A third potential constraint is the possible effect of a new signal on roadway safety. U.S. experience with signalized crossings of off-street busways with other roadways has been that a number of bus–vehicle crashes have occurred at these locations (Diaz and Hinebaugh 2009), particularly in the first year after installation. Driver expectancy issues may be at the root of the crashes, whether from not expecting two non-coordinated signals in short succession or from becoming accustomed to not having to stop for the signal due to relatively low bus headways. Therefore, a traffic signal installed specifically for buses would preferably have sufficient turning bus, pedestrian, and minor-street traffic volumes to require major street traffic to stop during most signal cycles so that major street drivers anticipate the potential need to stop as they approach the signal.

Benefits

Traffic signals specifically for buses are typically installed to address issues with buses turning left onto, turning left from, or crossing major streets and experiencing substantial delays doing so. A traffic signal could reduce bus travel time and travel time variability, but the specific benefits are highly site-specific and would need to be determined by a traffic engineering study. A traffic signal provides a new signalized pedestrian crossing opportunity, thereby improving pedestrian mobility in the area. A traffic signal installed in Calgary, Alberta, on a divided roadway stops traffic in the opposing direction only when a left-turning bus arrives, saving buses up to 90 s compared to waiting for a gap in traffic to make their turns (Jordan et al. 2010).

Cost Considerations

- **Planning and coordination costs.** Moderate to high. A traffic analysis would be needed to evaluate the intersection's current operations (including evaluating the effects on traffic progression) and how they would change with the presence of a new signal. An experimentation request entails additional study requirements (see Appendix D). If the signal would stop major street traffic infrequently, additional traffic control measures (e.g., signs) and motorist outreach programs may need to be considered (Diaz and Hinebaugh 2009).
- **Capital costs.** High—to install a new traffic signal and potentially make ADA-related improvements such as curb ramps if not already provided.
- **Maintenance costs.** Moderate, involving added costs for operating and maintaining the signal.
- **Bus operations costs.** Potential savings from reductions in travel time and travel time variability.
- **Other user costs.** Will likely increase delay to general traffic.

Implementation Examples

Canadian examples include those in Halifax, Nova Scotia (Corby et al. 2013); Calgary, Alberta (Jordan et al. 2010); Edmonton, Alberta; and Vancouver, British Columbia. In the United States, busway crossings have been signalized in conjunction with the South Dade Busway in Miami, Florida, and the Orange Line in Los Angeles, California (Diaz and Hinebaugh 2009). The Lymmo BRT line in Orlando, Florida, includes a signalized bus exit from a parking garage used in part as a park-and-ride facility.

Implementation Guidance

Before pursuing a traffic signal option, first consider whether rerouting buses to avoid the intersection is a feasible option. If not, an engineering study will be required to evaluate the need for a signal, the impacts of the signal on all roadway users, and potential impacts (positive and negative) on roadway user safety. If a signal would not be warranted on the basis of current

MUTCD warrants, an experimentation request would need to be prepared and approved by the FHWA to allow its use in the United States until such time that the MUTCD permits the use of signals specifically for buses. Note that a standard FHWA condition of approval is that the jurisdiction agrees to remove the installation (in this case, the signal) if the FHWA determines that the experiment is unsuccessful.

Additional Resources

- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—Chapter 4C discusses traffic control signal needs studies. A section of FHWA's MUTCD website describes the steps involved in the experimentation process: http://mutcd.fhwa.dot.gov/condexper.htm.

6.13 Traffic Control Enforcement

Description

Automated or manual techniques to enforce traffic laws essential for the successful operation of certain transit-supportive roadway strategies.

Purpose

The benefits of certain strategies can only be realized if other motorists comply with the traffic control devices used to provide preferential treatment to transit vehicles. Enforcement efforts provide a consequence when motorists do not comply with the device indications or regulations, and these efforts thereby make it more likely that the devices will be respected and the strategy will be effective.

Applications

Typical enforcement activities relate to:

- Enforcing turning movement restrictions for non-transit vehicles (Section 6.1, Section 6.2);
- Enforcing yield-to-bus laws (Section 6.3);
- Enforcing non-transit vehicle usage of bus lanes (Section 8.1), queue jump lanes (Section 6.10), and bus-only links (Section 7.7); and
- Enforcing parking and stopping restrictions associated with bus lanes (Chapter 8).

Enforcement can take place through traditional enforcement efforts involving parking enforcement staff or law enforcement officers. If permitted by local laws, photo or video enforcement can be an effective way to enforce bus-only links and bus lanes.

Companion Strategies

See the Applications section for a list of typical strategies requiring enforcement. Designing transit-supportive roadway strategies to be self-evident or self-enforcing to the extent possible, such as by employing painted bus lanes (Section 7.4), can reduce the need for active enforcement.

Constraints

Enforcing traffic laws that affect bus operations may be a lower priority for the local police department than enforcing laws that affect traffic safety or addressing community crime issues. State and local laws may need to be changed to permit the use of photo or video enforcement for transit-related purposes.

Benefits

Enforcement maximizes the benefit of transit-supportive roadway strategies that require other roadway users to respect the traffic controls that provide preferential treatment for buses. Without enforcement, the investments made in implementing these strategies may not pay off, and support for implementing other strategies in the future may be reduced. A Transport for London study (2006) of automated bus lane enforcement found that through enforcement, bus lane violations had been reduced by 85% and bus delays in bus lanes reduced by 15%. New York City credits automated bus lane enforcement as one of the factors behind a 15% to 23% improvement in bus speeds on three BRT routes (New York City DOT 2012), with the bus lanes themselves and stop consolidation being other major factors.

Cost Considerations

- **Planning and coordination costs.** High. A transit agency's own police force, if one exists, may be able to conduct enforcement, or coordination with local police departments may be necessary (or both). Part-time bus lanes (Section 8.1) will require coordination with towing companies to ensure that the lanes are clear of parked vehicles when in operation. For photo and video enforcement, agency staff time will be required to work with state legislators and local jurisdictions to authorize the use of automated enforcement, and public outreach will be needed to inform motorists about the new enforcement techniques. Depending on the type of strategy being enforced, other stakeholders may include business owners (for parking restrictions), neighborhood organizations (for bus-only links and turn restriction exemptions), district attorneys, and traffic court judges (AASHTO 2014).
- **Capital costs.** Potentially none (traditional enforcement) to high on a per-site basis (automated enforcement). AASHTO (2014) suggests the potential need to incorporate enforcement areas (e.g., extended-length pullouts) into bus lane projects.
- **Maintenance costs.** Potentially none (traditional enforcement) to moderate (added costs to maintain camera equipment). Traffic control devices (e.g., signs and markings) will need to be adequately maintained for rules to be enforceable.
- **Bus operations costs.** For traditional enforcement, the costs will depend on how often enforcement activities are undertaken and who performs them (e.g., local police departments, who may wish to be reimbursed for their costs, or transit agency police, who may need additional staff to add traffic control enforcement efforts to their existing duties.) For automated enforcement, there may be significant costs associated with processing violations, and these may be able to be recouped from the collected fines, depending on how the authorizing law is written.
- **Other user costs.** Strict enforcement of parking and delivery activities may affect local residents and businesses.

Implementation Examples

The New York State legislature granted New York City DOT and MTA the ability to install bus lane enforcement cameras on specified SBS routes. As of 2012, New York City DOT had installed cameras at 20 locations on three bus routes. Between April 2011 and March 2012, the cameras, in total, recorded approximately 6,000 bus lane moving violations per month, of which 14% were challenged, with 17% of the challenges being upheld, which is equivalent to 2% of all violation notices issued. As of 2012, the system had accrued about $2.6 million in capital costs and $860,000 in operating costs, which were offset by over $7.5 million in collected fines. Additionally, MTA installed in-bus cameras on six buses on one SBS route as a pilot project to record parking violations in bus lanes. A parking violation was determined to occur when the same vehicle was photographed by successive camera-equipped buses. The agencies considered the enforcement program to be a success in terms of covering its cost and in contributing to improved bus speeds and improved passenger perceptions of service reliability (New York City DOT 2012).

In 2007, the California legislature granted San Francisco the ability to conduct a pilot test of video enforcement of bus lane parking violations through 2011, which was subsequently extended through 2015. Video cameras were installed on 30 buses, with the footage reviewed by two parking control officers. Over 3,000 citations were issued in 2011, resulting in over $300,000 in fines. No information was provided about the cost of the program (SFMTA 2012).

Implementation Guidance

Enforcement begins by clearly informing motorists of the presence of the traffic control through clearly visible signs and pavement markings. These measures help reduce bus lane and other traffic control violations by inattentive motorists.

Regular enforcement efforts, in combination with sufficiently high fines, are necessary to deter willful violators. Posting the fine amount has been shown to be effective in reducing violations. In the absence of automated enforcement, enforcement efforts will need to be targeted to specific facilities at specific times (AASHTO 2014). This approach allows a large percentage of the motorists who regularly violate the traffic control at those locations to be caught, and it is visible—and thus potentially effective as a deterrent—to other roadway users.

Automated enforcement allows many bus facilities to be continually monitored and can recoup enforcement costs if agencies are allowed to keep some or all of the fines collected. To be effective in discouraging repeat offenses and to preserve a public perception that the enforcement is being conducted to allow buses to operate as efficiently as possible as opposed to being a revenue generator, violation notices should be sent out as soon as possible after the violation so that recipients can still remember what they were doing at the time. It is particularly important from a public relations standpoint to make sure that cameras are placed where there is no question that the law is being violated (a particular issue where vehicles are allowed to enter the bus lane to make right turns) and that the system can differentiate between legal and illegal bus lane uses.

Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.5.7.5 describes the weave-assist application of pre-signals, described as an “advance stop bar for bus left turns.”
- *2012 Bus Lane Camera Enforcement Update Report* (New York City DOT 2012)—this report summarizes how New York implemented its enforcement program, including its outreach and education efforts.

CHAPTER 7

Infrastructure Strategy Toolbox

This chapter is the third of four toolbox chapters presenting potential strategies for improving bus speeds and reliability. The strategies presented in this chapter focus on physical changes to the roadway that can improve bus operations. Bus lanes are also a type of infrastructure strategy, but given the wide variety of ways they can be implemented, they are discussed separately in Chapter 8.

Chapter 7 defines and discusses the following strategies:

- Modifying speed humps,
- Lengthening bus stops,
- Bus shoulder use,
- Red-colored pavement,
- Curb extensions,
- Boarding islands, and
- Bus-only links.

The introduction to Chapter 5 describes how each strategy section is organized.

7.1 Speed Hump Modifications

Description

Speed bumps and humps along bus routes are replaced with bus-friendlier versions.

Purpose

Speed bumps and humps that are relatively short (e.g., 3 to 6 ft long) force buses to slow to speeds (e.g., 15 mph or less) that are much slower than the street's posted speed to avoid uncomfortable (or dangerous, for standing passengers) jolts to passengers and damage to the bus's suspension. Because buses accelerate more slowly than automobiles, they experience more delay from speed bumps. The bus acceleration and deceleration associated with speed humps also consumes more fuel and can create noise impacts to adjacent land users (TransLink 2002, TriMet 2005, BC Transit 2010). Replacing them with alternative designs that buses can traverse at the street's posted speed, as well as avoiding installing new speed humps along bus routes, can avoid these impacts.

Applications

Any short speed bump or hump along a bus route is a candidate for this strategy. Bus-friendlier alternative designs include:

- **Speed tables.** Speed tables are longer (e.g., 22 ft), flat-topped elevations of the roadway surface that raise the entire vehicle wheelbase and can also be used in conjunction with raised pedestrian crosswalks; and
- **Speed cushions.** Speed cushions are speed humps or speed tables that provide wheel cutouts that allow wider-wheelbase vehicles such as buses and emergency vehicles to pass without a bump while still reducing automobile speeds (National Association of City Transportation Officials [NACTO] 2013).

Malmö, Sweden, has used a modified speed table design (pictured at the beginning of this section) on transit and emergency vehicle routes where the roadway surface is raised quickly on the entry side, similar to a speed table, but is then lowered gently back to grade on the departure side.

Companion Strategies

This strategy can be implemented by itself or as part of a package of transit-supportive roadway strategies along a street.

Constraints

Roadway agency design manuals may need to be updated to allow the use of alternative designs. Roadway agency traffic-calming policies may need to be updated to discourage the installation of new speed humps along bus routes.

Benefits

Replacing speed humps with bus-friendlier designs can retain the desired traffic-calming effect while improving bus passengers' comfort, improving bus fuel economy (by avoiding the need to accelerate after the hump), and reducing noise impacts in the vicinity of the speed hump. Emergency vehicles will also benefit from bus-friendly speed hump designs.

Cost Considerations

- **Planning and coordination costs.** Moderate. Up-front coordination will be needed with the roadway agency to approve bus-friendlier traffic-calming designs or to develop policies discouraging or preventing speed hump use on bus routes or designated transit streets. Neighborhood outreach is suggested when changing an existing speed hump to a bus-friendlier design. Emergency responders may be supportive of speed hump changes that allow faster emergency vehicle response times.
- **Capital costs.** Low to moderate costs to remove or replace the speed hump.
- **Maintenance costs.** A bus-friendlier design may reduce pavement damage caused by buses decelerating and traveling over a speed hump.
- **Bus operations costs.** Potential savings from reductions in travel time and improved fuel economy.
- **Other user costs.** Removing an existing speed hump may result in higher traffic speeds along the street before and after where the hump was located, which has potential safety impacts.

Implementation Examples

No U.S. or Canadian examples were identified in the literature. As noted previously, Malmö, Sweden, has implemented bus-friendlier speed tables.

Implementation Guidance

U.S. and Canadian transit agency design guidelines discourage the use of speed humps along transit routes for the reasons described in the Purpose section. Alternative traffic-calming strategies should be investigated first. When speed humps must be used, it is suggested that they:

- Not be installed near bus stops since passengers may be moving to or from their seats during this time,
- Provide as long a distance as possible (e.g., 22 ft) between the slope up and the slope down or be designed such that buses avoid the bump (e.g., a speed cushion),
- Provide at least 600 ft between successive bumps, and
- Be located so that buses can traverse them at a 90-degree angle (e.g., not near bus stops) (TransLink 2002, TriMet 2005).

Additional Resources

- *Urban Street Design Guide* (NACTO 2013)—Pages 54 and 55 describe speed tables and speed cushions, respectively.

7.2 Bus Stop Lengthening

Description

A bus stop's length is increased to allow it to serve more (or longer) buses simultaneously.

Purpose

If more buses want to use a stop at one time than space exists to allow, the other buses have to wait in the street until space opens up at the stop. This delays both buses and general traffic. Matching a bus stop's capacity to serve buses to the scheduled number of buses can minimize the potential for bus stop failure to occur.

Applications

Bus stop failure can occur for several reasons: (1) the number of buses scheduled to use the stop over the course of an hour exceeds the bus stop's capacity, (2) the number of buses scheduled to use the stop over a short period of time exceeds the number of loading areas provided, or (3) schedule irregularities and bus bunching result in more buses arriving at a time than the stop can accommodate. The second and third reasons can be addressed first through schedule adjustments and transit agency actions to improve bus reliability and do not necessarily require lengthening stops. The first reason cannot be addressed by scheduling alone and requires lengthening bus stops to provide more capacity, changing route patterns so that fewer buses use the stop, or both.

Companion Strategies

Bus stop lengthening may need to be considered when stops are consolidated (Section 5.2) since the increased passenger activity at the remaining stops will increase bus dwell times and thus reduce the number of buses that a bus stop can accommodate during an hour. Bus stops may also need to be lengthened when longer buses are introduced (Section 5.5). If a bus stop cannot be lengthened at its current location, it may need to be relocated (Section 5.1).

Constraints

Lengthening bus stops may result in a loss of on-street parking. It may not be feasible if driveways, alleys, or intersections are located close to the stop. If one stop requires lengthening, there is a good chance that other stops with the same number of loading areas, where buses dwell as long or longer, will also require lengthening.

Benefits

When bus stop failure occurs, the delay experienced by a bus can last up to the dwell time and subsequent traffic signal delay time of the buses already using the stop. Lengthening the bus stop will reduce the probability that failure occurs, thereby improving travel time variability. When the stop is offline (e.g., in the parking lane or at a pullout), general traffic delay and travel time variability will improve to the extent that bus stop failure is reduced. The TCQSM (Kittelson & Associates et al. 2013) can be used to estimate how often bus failure occurs, or AVL data or field measurements can be used to determine bus delay directly.

Cost Considerations

- **Planning and coordination costs.** Relatively low on a per-site basis. Lengthening a stop will need to be coordinated with the appropriate roadway agency. It is also desirable to engage adjacent property owners in advance about potential negative impacts to them (e.g., loss of parking).
- **Capital costs.** Typically relatively low on a per-stop basis, consisting of moving parking signs and making any required ADA improvements such as a landing pad. The need for concrete paving at the bus stop to reduce bus-caused pavement damage may also be considered. Costs will be higher when curb lines or parking meters need to be moved to accommodate a longer stop.
- **Maintenance costs.** No significant change in costs.
- **Bus operations costs.** Reduces bus travel time variability.
- **Other user costs.** For offline stops, reduced delay for motor vehicles that would otherwise be blocked by buses waiting in the travel lane to enter the stop. Potential loss of on-street parking.

Implementation Examples

Thirteen of 59 transit agencies responding to a survey reported increasing bus stop length to improve bus speeds (Boyle 2013).

Implementation Guidance

The TCQSM (Kittelson & Associates et al. 2013) can be used to estimate hourly bus stop capacity given a desired failure rate and provides recommended failure rates for different land use contexts (e.g., downtown, suburbs). If the calculated hourly bus stop capacity is adequate, yet bus stop failures occur significantly more often than the failure rate used in the calculation, this is a sign of either schedule reliability problems or scheduling issues over a short period of time that cause too many buses to arrive at the stop at once. In these cases, the transit agency may wish to address the cause of the problem first (scheduling or reliability) rather than the symptom (bus stop failure). If the calculated hourly bus stop capacity is inadequate, the capacity of other bus stops along the street with the same or longer dwell times should also be checked since fixing the problem at one stop may simply move it to another stop, and it would be preferable to address all of the corridor or route's capacity issues at one time.

If capacity is inadequate, but lengthening stops is physically or politically infeasible, the transit agency may wish to consider skip-stop operations, where buses are divided into groups and assigned specific sets of stops to serve (e.g., every other existing stop). This is a form of stop consolidation (Section 5.2) where the number of stops served by a given route is reduced, although the physical number of stops is unchanged. The available bus stop capacity can thus serve a greater number of buses (up to nearly twice as many) compared to having all buses serve all stops. The TCQSM describes skip-stop operations and analyzing their capacity in detail.

Additional Resources

- *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition (Kittelson & Associates et al. 2013)—Chapter 6 provides analytical methods for estimating bus stop capacity and describes skip-stop operations and their impact on bus capacity.
- TCRP Project A-42, "Minutes Matter: A Guide to Bus Transit Service Reliability," which began in 2015 with the objective of providing comprehensive guidance to transit agencies on ways to improve their bus reliability.

7.3 Bus Shoulder Use

Description

Buses are allowed to use roadway shoulders during peak periods.

Purpose

To avoid congestion in the general traffic lanes and thereby gain a speed advantage on general traffic.

Applications

A typical arterial roadway application is a suburban divided highway with occasional signalized intersections. Minneapolis uses the following criteria to identify potential corridors:

- Peak-period running speeds between intersections are regularly 35 mph or less for general traffic, or intersection approaches regularly have continuous queues during peak hours;
- A minimum of six transit buses per day are likely to use the shoulder (i.e., are scheduled to operate during periods when congestion occurs);
- The anticipated time savings must be at least 8 bus-minutes per mile per week; and
- The shoulder must be at least 10 ft wide, although pinch points where buses merge back into regular traffic are permitted (Martin et al. 2012).

Companion Strategies

Bus shoulder use can be implemented in smaller sections as part of queue jump (Section 6.10) and queue bypass (Section 8.6) projects. Transit signal priority (Section 6.7) can be implemented in conjunction with shoulder operation. Bus stops are typically located on right-turn channelization islands (Section 7.6) at signalized intersections. Periodic enforcement efforts (Section 6.13) may be required to ensure that only authorized vehicles use the shoulder.

Constraints

The shoulder must be sufficiently wide to permit buses to operate. *TCRP Report 151: A Guide for Implementing Bus On Shoulder (BOS) System*s (Martin et al. 2012) suggests a minimum shoulder width of 10 ft, based on successful freeway and arterial implementations in the United States and Canada. Occasional pinch points where the shoulder narrows, such as on bridges, may be tolerated, but buses will need to merge into the adjacent general traffic lane at those points. The shoulder must be capable of supporting the weight of the number of buses expected to use it. Shoulder use by buses may require changes to state traffic laws, and individual projects may require exceptions to roadway agency design standards. Bus shoulder operation on roadways with designated bicycle facilities or routes on the shoulder is not suggested.

Benefits

The potential benefit will depend on how long the general traffic lanes are congested and how far that congestion extends. Travel time surveys of three directional arterial corridors in the Minneapolis region indicated average time savings of 1.5 to 2.5 min plus reductions in travel time variability. For safety reasons, buses are typically limited to traveling 10 to 15 mph faster than general traffic while using shoulder lanes, which limits how much of a travel time benefit can be achieved. Passengers perceive the travel time savings (and sometimes perceive greater savings than actually occur) and also perceive improved travel time reliability (Martin et al. 2012). Shoulder operation on an arterial expressway in Calgary, Canada, saves buses up to 15 min during peak periods (Jordan et al. 2010).

Cost Considerations

- **Planning and coordination costs.** High. The suitability of the corridor will need to be evaluated with respect to safety and operations at intersections and access points, shoulder width, and pavement strength. New signs will need to be developed the first time a shoulder facility is implemented by a roadway agency, and exceptions to roadway agency design policy will need to be documented (or the policy updated with provisions for shoulder use). Coordination with law enforcement will be required. Public outreach is desirable, particularly for the first implementation in an area. Training will be needed for the bus drivers who will use the facility.
- **Capital costs.** Moderate to high. At a minimum, new signs will be required along the length of the corridor. Other potential costs may be for relocating or upgrading bus stops and pedestrian access routes to those stops, relocating bicycle facilities in the corridor, widening the shoulder, strengthening the shoulder, and constructing pullouts for enforcement activities.
- **Maintenance costs.** More frequent sweeping may be required to ensure the shoulder is free of debris.
- **Bus operations costs.** Reduces bus travel times and travel time variability. Because shoulder bus use is often implemented on long-distance commuter bus routes operating on suburban highways, buses frequently make only one peak-period trip, and the time savings may therefore not translate into using the bus for additional trips (Martin et al. 2012). There may be additional fuel economy savings related to avoiding stop-and-go traffic.
- **Other user costs.** In general, there is no impact to other roadway users (Martin et al. 2012).

Implementation Examples

As of January 2011, shoulder operation on arterial roadways had been implemented in the following locations in the United States:

- Minneapolis region, Minnesota (many corridors);
- Burtonsville, Maryland (U.S. 29);
- Kenmore, Washington (SR 522); and
- Mountainside (U.S. 22) and Old Bridge (U.S. 9), New Jersey (Martin et al. 2012).

Shoulder operation is also used on a section of Crowchild Trail in Calgary, Alberta, that experiences queues up to 1.5 km (0.9 miles) long during peak periods (Jordan et al. 2010).

Implementation Guidance

TCRP Report 151 provides comprehensive guidance on the planning, design, and operational considerations associated with implementing bus shoulder operations.

Additional Resources

- *TCRP Report 151: A Guide for Implementing Bus On Shoulder (BOS) System*s (Martin et al. 2012)—comprehensive implementation guidance, accompanied by case studies of successful implementations.

7.4 Red-Colored Pavement

Description

All or selected segments of a bus lane are indicated with red-colored pavement as a supplement to the normal bus lane signs and striping.

Purpose

To improve the conspicuity of the bus lane and thereby reduce the number of bus lane violations by unauthorized vehicles.

Applications

This strategy can be considered anywhere a roadway lane is reserved exclusively or primarily for buses. The greater the number of buses using the bus lane, the greater the impact of bus lane violations on bus operations and thus the greater the potential benefit offered by the strategy. The colored pavement can be applied solely at the start of a lane (e.g., to guide turning vehicles away from the bus lane), only in the sections where only buses are permitted (e.g., to indicate where vehicles may enter the lane to make right turns), or for the full length of the lane, including sections where other vehicles are permitted by law to briefly enter the lane (e.g., to enter or cross the lane to make a right turn, to stop to immediately pick up or drop off passengers); however, it should be applied consistently within a jurisdiction.

Companion Strategies

Red-colored pavement can be used in combination with turn lanes designated exclusively for buses (Section 6.1), queue jump lanes designated exclusively for buses (Section 6.10), bus-only links (Section 7.7), and most types of bus lanes (Section 8.1) except shared bus and bicycle lanes (Section 8.3).

Constraints

At the time of writing, the use of red-colored pavement for transit was expected to be permitted in the next edition of the MUTCD, which is anticipated to be published in 2017. Until such time that it appears in the MUTCD (or the FHWA issues an Interim Approval for its use), roadway agencies in the United States will need to submit an experimentation request to FHWA, and have it approved, to be able to use this strategy. An experimentation request template is provided in Appendix D.

New York City's testing of different forms of red coloring treatments found no treatment that lasted more than one year on Portland cement concrete surfaces (Carry et al. 2014).

Benefits

Red-colored pavement would be expected to reduce the number of bus lane violations. A study of 61 bus lane segments in New York City found no significant difference in the occurrence of obstructions (other roadway users legally or illegally entering the lane) when comparing lanes with white bus lane pavement markings only to those lanes supplemented with red coloring (Safran et al. 2014). However, red coloring was highly correlated with interior bus lanes, while lack of red coloring was highly correlated with curbside bus lanes, and interior bus lanes showed significantly lower obstruction rates. In addition, the same study found the bus driver used red lanes 52% more often than non-red lanes, indicating a greater degree of bus driver confidence in red-colored lanes being unobstructed. More research is needed to quantify the contribution of red-colored pavement to reductions in bus lane violations and reductions in bus delay and travel time variability.

Cost Considerations

- **Planning and coordination costs.** High at present, due to the need for FHWA experimentation and the corresponding documentation. Once incorporated into the MUTCD, the strategy would require roadway agencies to develop policies on when to apply red-colored pavement. A moderate level of planning and coordination would be needed when applying the strategy to existing bus lanes, but a relatively small increment of additional planning would be needed when incorporating the strategy into a new bus lane project.
- **Capital costs.** Moderate to high since a large surface area may need to be colored.
- **Maintenance costs.** Will increase maintenance costs since the coloring will need to be reapplied periodically.
- **Bus operations costs.** Expected to help reduce bus travel times and travel time variability, but little quantitative information was available at the time of writing.
- **Other user costs.** May reduce the likelihood that drivers will inadvertently drive in a bus lane. May make bus lanes easier to enforce due to the extra conspicuity provided by the red coloring.

Implementation Examples

As of early 2015, U.S. implementations included New York City, San Francisco, Chicago, and Seattle. This strategy is used in many cities internationally.

Implementation Guidance

The proposed MUTCD language indicates that travel lanes "used by public transit vehicles and other modes" (e.g., shared bus and bicycle or bus and taxi lanes) "should not use red-colored pavement." The proposed language also indicates that red-colored pavement "shall be applied only in lanes, areas, or locations where general-purpose traffic is generally prohibited to use, queue, wait, idle, or otherwise occupy the lane area or location where red-colored pavement is used" and that "regulatory signs shall also be used when it is determined that other vehicles will be allowed to enter the lane to turn or bypass queues" (NCUTCD 2014b). As proposed, this language seems to indicate that red-colored pavement could be used in sections where specified classes of vehicles (e.g., right-turning vehicles) are allowed limited access to the lane but not in sections where general traffic has unrestricted use of the lane at all times nor for long sections of a lane that allow shared use by other modes.

Red-colored pavement is considered supplemental to the signs and pavement markings (e.g., solid white stripe, bus-only markings) that are required to enforce bus lanes. As pavement markings are allowed for part-time bus lanes with signs indicating the times the bus lane is in effect, it follows that red-colored pavement would also be allowed for part-time bus lanes.

The use of red-colored pavement may depend on local laws governing bus lanes. If other vehicles are permitted to use the lane to make a right turn at the next driveway or cross street, then non-transit vehicles may be present at any point along the bus lane, and using red coloring for the entire lane may be appropriate to discourage through-traffic use. On the other hand, if vehicles are only allowed to enter or cross the lane at designated points (e.g., where a right-turn lane begins), then ending the coloring at that point would provide a visual cue to direct motorists to the desired location for them to enter or cross the lane. To date, no research has been done on the comparative effectiveness of different red-colored pavement applications (e.g., for a short distance after an access point or for the full length of the lane, not where the bus lane becomes a right-turn lane).

Carry et al. (2014) describe the results of durability and skid-resistance testing of different colored pavement treatments. They found that "red epoxy-based street paint, an epoxy with red aggregate product, and a red asphalt concrete-based micro surface performed well across all field and laboratory tests." They found no treatment that lasted more than 1 year when applied to Portland cement concrete surfaces.

Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.5.6.4.2 describes colored pavement applications.
- Red Bus Lane Treatment Evaluation (Carry et al. 2014)—paper describing New York City's efforts to test the durability and skid resistance of different types of colored pavement treatments.

7.5 Curb Extensions

Description

Curb extensions (bus bulbs, bus nubs) extend the curb and sidewalk out to the edge of the parking lane.

Purpose

This strategy allows buses to stop in the travel lane and thereby avoid delay waiting for a gap in traffic (reentry delay) when leaving the stop. When used at intersections, it reduces the pedestrian crossing distance, which reduces pedestrian exposure to traffic conflicts. At signalized intersections, it also reduces the time required to serve pedestrian movements, which may allow a shorter traffic signal cycle length, which can also reduce bus delay.

Applications

Curb extensions are particularly suited to areas with high-density development, where the percentage of people moving through the corridor as pedestrians or in transit vehicles is relatively high in comparison with the percentage of people moving in automobiles. On-street parking is a prerequisite since curb extensions are constructed within the area used by the parking lane.

Companion Strategies

Curb extensions can be used in combination with interior bus lanes (Section 8.4). Yield-to-bus laws (Section 6.3) are another way of tackling the problem of reentry delay.

Constraints

Curb extensions affect street drainage patterns, and drainage may need to be reworked to prevent water ponding issues. When used at intersections, they reduce the turning radius available for larger vehicles, which may require restrictions on right turns or moving the side-street stop bar away from the intersection to provide more room for larger turning vehicles. If bicycle facilities exist, consideration will need to be given to how to route bicycles around stopped buses (see Appendix C) (Fitzpatrick et al. 2001). The ability to match the roadway and sidewalk cross-slopes so that a low-floor bus's wheelchair ramps can deploy at an ADA-acceptable slope should be carefully considered (TriMet 2010).

Benefits

The potential benefit from curb extensions is high since reentry delay can range from 1 to 12 s, depending on traffic volumes, at bus stops well away (i.e., at least ¼ mile downstream) from traffic signals, and can be considerably higher at stops at or near signals (Kittelson & Associates et al. 2013). A Florida study recorded average reentry delays of over 30 s at some bus stops (Zhou et al. 2011). However, as with any strategy involving spot locations, the sum of the delay benefit for a route or along a street will generally be less than the sum of the individual bus stop delay benefits since the delay saved at one stop is sometimes lost at a downstream traffic signal. See Section 4.4 for more information.

A study of curb extensions along a four-lane street in San Francisco found that average bus speeds within the block where the stop was located improved by an average 0.2 to 2.2 mph, while average vehicle speeds within the block improved by an average 4.5 to 8.5 mph. Over the length of a 2,400-ft section of the street containing seven bus stops and six traffic signals, average bus speeds improved by 0.5 mph, while average vehicle speeds improved by 3 to 7 mph. Reasons given for the improvement in vehicle speeds are that 48% to 72% of buses would stop partly in the travel lane (i.e., not pull up to the curb) prior to the construction of curb extensions and thus disrupted traffic flow, and that buses would sometimes use both travel lanes when exiting the stop (Fitzpatrick et al. 2001). Following the construction of curb extensions, bus stopping patterns would have become more predictable to motorists, and buses would not have encroached on the second lane. A simulation study of the same corridor, where buses did pull to the curb in the before case, found smaller effects: speeds through the corridor improved by 0 to 2 mph for both vehicles and buses (Fitzpatrick et al. 2001).

When used at intersections, curb extensions shorten the pedestrian crossing distance, thus reducing the amount of time pedestrians are exposed to conflicts with other road users and, potentially, the amount of time that other road users are delayed by pedestrians crossing. At signalized intersections, the reduced crossing distance results in less flashing "Don't Walk" time; this time can be used for longer walk times (reducing pedestrian delay) or to decrease the traffic signal cycle length (if minimum pedestrian phase lengths determine the length of side-street phases), potentially resulting in reduced delay for all intersection users. A review of state DOT design manuals found that while most did not include sections covering transit-supportive roadway strategies, a number provided the option of using curb extensions as a strategy to benefit pedestrians.

A study of curb extensions in San Francisco found that curb extensions provided both a better bus stop waiting environment (in terms of the space available per waiting passenger) and better adjacent sidewalk flow by giving bus passengers a place to wait other than the sidewalk (Fitzpatrick et al. 2001). The added space can be used to add bus stop amenities such as bus shelters, thereby reducing the potential for waiting passengers to congregate in front of businesses' display windows and doors.

Curb extensions can increase the amount of on-street parking provided since the parking lane can be continued up to the start of the bus stop. Without a curb extension, parking needs to be prohibited before or after the stop (or both) to give buses the opportunity to maneuver from the travel lane to the curb and vice versa (Kittelson & Associates et al. 2013).

Cost Considerations

- **Planning and coordination costs.** Moderate. A traffic analysis may be needed to evaluate the impact of the curb extension on vehicular traffic. Civil engineering plans will need to be developed to address street drainage modifications. Outreach to adjacent businesses is suggested, particularly when installing shelters that may block views of businesses' signs from the street (Fitzpatrick et al. 2001).
- **Capital costs.** Moderate, with the largest portion of the cost involving drainage changes and, potentially, utility relocations (Danaher 2010). There will be added costs if bicycle facilities are to be relocated around the bus stop.
- **Maintenance costs.** No significant change expected.
- **Bus operations costs.** Reduces bus travel time and travel time variability.
- **Other user costs.** On streets with one lane of travel per direction, will tend to increase vehicular delay, with the extent of the delay dependent on bus frequencies, dwell times, traffic volumes, and whether the stop is located at a signalized intersection (because traffic might need to stop anyway). On streets with two or more travel lanes per direction, one study found a decrease in motorized traffic delay (Fitzpatrick et al. 2001).

Implementation Examples

A survey of 52 transit agencies found that 25% had implemented at least one curb extension (Danaher 2010). Portland, Oregon; San Francisco, California; Seattle, Washington; and Vancouver, Canada, are among the cities that have widely implemented curb extensions and developed formal guidelines on their use (Fitzpatrick et al. 2001).

Implementation Guidance

Conditions supportive of installing curb extensions include:

- Presence of full-time curbside parking;
- Near-side or midblock stop locations;

- Relatively low traffic speeds (35 mph or less);
- Low to moderate traffic volumes (<500 vehicles per hour per lane in the same direction);
- Two or more travel lanes in the direction of travel, to allow passing (desirable but not essential);
- Relatively high sidewalk or crosswalk usage or relatively high passenger volumes using the stop (e.g., is sidewalk flow or access to adjacent businesses affected by passengers waiting on the sidewalk?); and
- Relatively low right-turning volumes, particularly larger vehicles such as trucks and buses (Danaher 2010, Fitzpatrick et al. 2001).

Conditions requiring special attention include complex drainage issues, streets with bicycle facilities, and intersections where the right-turning traffic volume might require a right-turn lane (Danaher 2010). Far-side locations on streets with only one travel lane in the direction of travel are not recommended due to the potential for queues behind the bus to block the intersection.

A traffic analysis, based on expected bus frequencies, average dwell times, vehicular volumes, and estimated improvements in pedestrian crossing delay, can determine the typical level of queuing and vehicle delay that would be expected as a result of buses serving a stop with a curb extension. The TCQSM can be used to estimate the reentry delay saved by buses and their passengers. Appendix C of this guidebook provides guidance for accommodating bicycles at bus stops.

Additional Resources

- *TCRP Report 65: Evaluation of Bus Bulbs* (Fitzpatrick et al. 2001)—implementation examples and application guidance.
- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.2.2.2 provides guidance on curb extensions. The AASHTO guide's list of situations that are not recommended for transit is more auto-centric than this guidebook's; conditions that are not listed here (e.g., only one lane available in the direction of travel, low pedestrian volumes) may warrant analysis but should not by themselves disqualify a location from consideration. As with any other type of transit-supportive roadway strategy, the benefit provided to transit passengers and operators should be weighed against the cost of implementing the strategy, including disbenefits to other roadway users. Section 7.1.4.3 describes the benefits of curb extensions for pedestrians.

7.6 Boarding Islands

Source: © 2015 Google

Description

Bus stops on raised concrete islands within the roadway.

Purpose

Boarding islands are a supporting strategy that allows bus stops to remain at intersections when another strategy is implemented.

Applications

Figure 9 illustrates three potential applications for boarding islands. For simplicity in presenting the concept, bicycle facilities are not shown but can be incorporated into the design as discussed in the Implementation Guidance section.

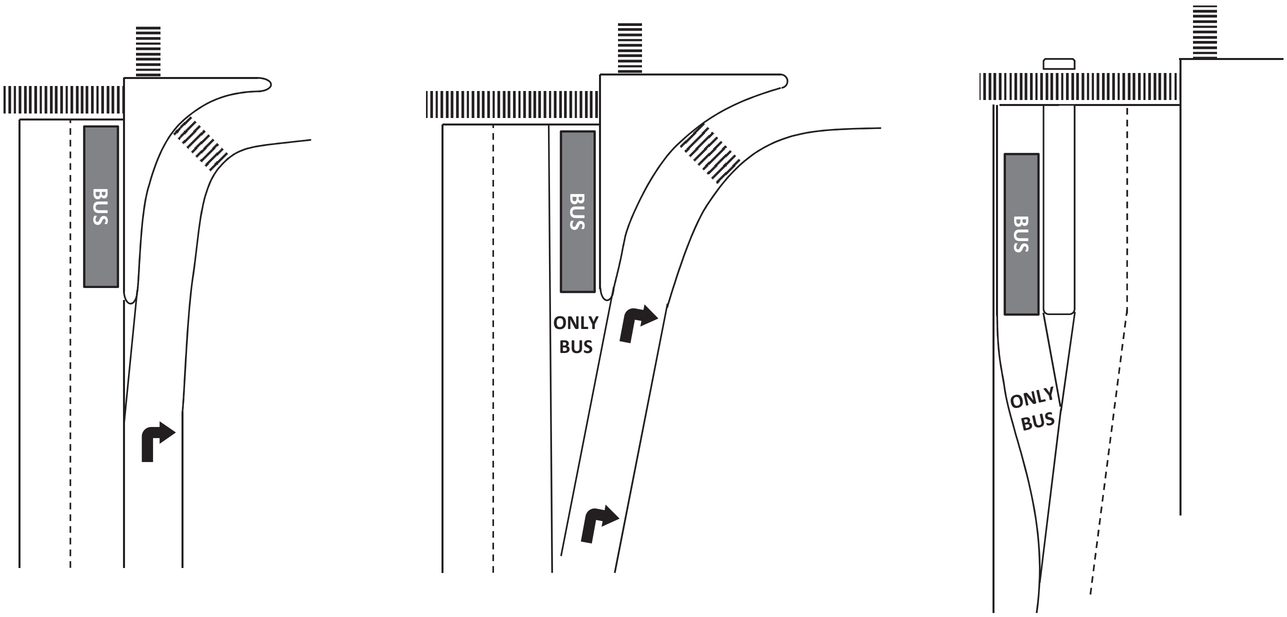


Figure 9. Illustrative boarding island configurations.

Figure 9(a) shows a boarding island on a right-turn channelizing island where buses stop in the travel lane to serve the stop. The island needs to be wide enough to provide at least the 8-ft by 5-ft clear area required by the ADA next to where the front door of a bus would stop. Not shown in the illustration, but also potentially needed, are bollards to protect the boarding area from errant vehicles and pedestrian fencing or similar barriers to limit pedestrian access to areas, as wanted.

Figure 9(b) shows a boarding island (in conjunction with a queue jump) located on a larger right-turn channelizing island. It is similar to the concept shown in Figure 9(a) but provides more passenger waiting area and allows buses to stop in a short bus lane.

Figure 9(c) shows a boarding island in the interior of the roadway and served by a short bus lane. The configuration shown in the illustration could support buses transitioning into a median bus lane (Section 8.7) beyond the intersection or buses making a left turn at the intersection. A similar configuration could support a left-side bus lane on a one-way street (Section 8.5). Space permitting, it would be possible to provide a conventional left-turn lane for general traffic to the left of the bus lane or on the right side of the boarding island; in the latter case, a bus-only signal phase (Section 6.9) would be required for buses departing the stop. The bus stop itself would be configured similarly to median bus stops on bus rapid transit lines by using a ramp connecting the platform to the crosswalk. As with the other boarding island configurations, the island would need to be at least 8 ft wide to provide the minimum required ADA clear area, and pedestrian fencing or other similar barriers may need to be considered.

A bus stop could also be provided on a large-enough right-turn channelizing island on the far side of an intersection. In this case, a short bus lane would be preferred so that buses could stop out of the traffic lanes without other vehicles possibly stopping behind them and blocking the intersection. Design considerations with this application include managing the area where cross-street right-turning traffic enters the main street and managing conflicts with buses exiting the bus stop.

Companion Strategies

This strategy supports bus-only signal phases (Section 6.9—for example, a bus left turn from a right-side lane), queue jumps (Section 6.10), most forms of bus lanes (Section 8.1), and other strategies that can be used in combination with queue jumps and bus lanes. For example, a short bus lane could be highlighted with red pavement coloring (Section 7.4).

Constraints

Sufficient space needs to be available on the island to provide the minimum required ADA clear area for each bus loading area provided at the stop. Potential sight-distance issues created by a bus shelter or stopped buses are suggested to be considered when placing bus stops on right-turn channelization islands. Right-turn channelization islands large enough to accommodate a bus stop are more likely to be found in suburban areas where right-of-way may be less constrained and where roadway designs provide larger vehicle turning radii.

Benefits

When the location of passenger generators or other considerations suggest the need for a near-side stop, it can be difficult to find a suitable location when a right-turn lane is provided. Right-turning traffic will delay buses trying to access a bus stop located at the stop bar, while a stop located prior to the start of the right-turn lane may require significant extra walking distance for most passengers and thereby discourage ridership. Placing a stop on a boarding island can allow the stop to be located at the intersection without buses experiencing the negative effects of the right-turning traffic.

Unless buses are equipped with doors on both the right and left sides, boarding islands are required when bus stops are to be provided along bus lanes located on the left side of the street.

In either case, the boarding island itself provides no special benefit; rather, it makes other strategies feasible while maintaining good access to bus service.

Cost Considerations

- **Planning and coordination costs.** Low to moderate for right-turn channelizing islands, depending on how much modification the island will require; sight distances will need to be evaluated. Moderate to high for channelizing islands elsewhere in the roadway due to the likely need to realign other travel lanes, but may be incorporated as part of a larger bus lane or roadway improvement project.
- **Capital costs.** Low (for existing right-turn channelization islands that require no modification) to high (new island construction and changes to the roadway). Pedestrian fencing, bollards, and MUTCD object markers may be required. Concrete paving at the bus stop to reduce bus-caused pavement damage may also be needed.
- **Maintenance costs.** Unchanged (for existing right-turn channelization islands that require no modification) to moderate increases (to replace or repair damaged bollards, fencing, etc.)
- Bus operations costs. No direct change.
- **Other user costs.** May reduce bus-caused delays to right-turning traffic when used in combination with a channelizing island.

Implementation Examples

- **San Francisco.** Examples of ADA-compliant boarding islands serving left-side bus lanes are Bush Street at the near side of Battery Street, Folsom Street at the far side of 2nd Street, Fremont Street at the near side of Market Street, and Beale Street at the far side of Howard Street. San Francisco is also constructing ADA-compliant interior boarding islands at some street-running light rail stops. Market Street has a number of examples of pre-ADA streetcar-era interior boarding islands.

- **New York.** An interior boarding island is used to serve a bus stop on the left side of White Plains Road at the Gun Hill Road subway station in the Bronx. At the time of writing, an interior boarding island was being considered for Third Avenue at East 57th Street in Manhattan. This island, in conjunction with an offset bus lane in the third lane from the right curb, would allow buses to avoid heavy right-turning traffic in the two right lanes and allow a stop to be placed within a six-block section of Third Avenue currently lacking stops (New York City DOT 2014).
- **Atlanta.** Bus stops are provided on right-turn channelizing islands in conjunction with queue jumps at several locations along Memorial Drive in suburban Atlanta.
- **Copenhagen, Denmark.** Two interior bus islands serve northbound buses along Øster Farimagsgade at Sølvgade in central Copenhagen, allowing buses to avoid significant bicycle and right-turning traffic while continuing to provide a stop at the intersection. At the street's northern end, a similar arrangement is used to create a near-side bus stop prior to the bus route turning left.

Implementation Guidance

General Considerations

Conditions supportive of installing a boarding island on a right-turn channelizing island include those discussed in this section.

- Suburban locations, which are more likely to have right-turn channelizing islands, due to greater potential right-of-way availability and higher-speed roadway design, compared to urban and downtown environments.
- Sufficient space on the island to accommodate the ADA-required clear area at the bus stop, passenger waiting area, bus shelter (if warranted by passenger volumes), and waiting areas for pedestrians using the crosswalks leading off the island.
- Passenger generator or transfer opportunities that suggest the need for a near-side stop.
- Desire to provide a queue jump (Section 6.10), bus-only signal phase (Section 6.9), or other near-side transit-preferential treatment.
- Ability to accommodate bicycle facilities that may be present on the street.
- For right-turning traffic, ability to address potential sight-distance issues caused by bus shelters or stopped buses.
- For a far-side channelizing island, space to provide a short bus lane and the ability to manage potential merging conflicts.

Interior boarding islands are necessary supporting infrastructure when bus stops are desired to be provided along interior, left-side, or median bus lanes. They need to be wide enough to provide the ADA-required clear area at the bus stop and need to provide an accessible route connecting to a pedestrian crosswalk leading away from the island.

With all types of boarding islands, consider the need to provide pedestrian fencing or similar barriers to control pedestrian movements, bollards to protect passenger waiting areas from errant vehicles, and the roadway agency's requirements for marking, signing, and striping raised islands in the roadway.

Bicycle Considerations

Boarding islands can be designed to accommodate bicycle traffic. When the boarding island is also a right-turn channelization island, the first consideration is managing the conflict between bicycles and right-turning traffic, typically by transitioning bicycle traffic to the left of the right-turn lane. NACTO (2012) provides several potential concepts. The next consideration is managing the bicycle–bus conflict. Options include:

- If the island is large enough, creating a channel through the island for the bicycle facility or raising the bicycle lane to the level of the island. In either case, the bicycle facility would separate the bus stop platform area from the remainder of the island. To minimize bicycle–pedestrian conflicts, the parallel crosswalk could be set back from the intersection by locating it to the right of the bicycle facility (as seen from the bicyclist point of view).
- If sufficient space exists, create a short shared bus and bicycle lane wide enough to allow bicycles to pass stopped buses.
- Continue an exclusive bicycle lane through the bus stop using a dotted lane marking to indicate that buses can cross into the bicycle lane to serve the stop.
- If no bicycle facility exists, shared-lane markings (sharrows) could be used to guide bicyclists through the bus stop area.

Additional Resources

- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—The guide discusses the potential for placing a bus stop on a right-turn channelization island if the island "is long and wide enough" (Section 5.1.1.2.1). The guide also suggests the possibility of providing right-side island platforms for left-side bus lanes on two-way streets by shifting the bus lanes into the median at bus stops and splitting the stops between the two sides of an intersection to reduce the total width required (Section 5.5.5.1).
- *TCRP Web-Only Document 66: Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies*—Appendix A presents the results of a literature review on boarding islands.

7.7 Bus-Only Links

Description

Bus-only links (bus gates, bus-only crossings, bus sluices) are short sections of roadway connecting public streets that can only be used by transit vehicles and other authorized vehicles (e.g., emergency vehicles).

Purpose

Bus-only links are typically used to provide direct bus access to areas where general traffic is not desired. Bus-only links:

- Provide bus, pedestrian, and bicycle access between neighborhoods with limited street connectivity by design;
- Maintain bus access through a neighborhood after a neighborhood traffic management program is implemented;
- Allow buses to make turns that are prohibited to general traffic (Section 6.1) due to cut-through traffic concerns or capacity constraints;
- Prioritize non-automobile traffic on a street by using a short bus-only link to eliminate through traffic while maintaining local traffic access on either side of the link; and
- Provide bus access to activity center areas (e.g., city centers, university campus areas) where private vehicles are restricted.

Applications

Bus-only links can be enforced in several ways:

- **Signs and pavement markings only.** Signs, or a combination of signs and pavement markings, prohibit general traffic but allow transit vehicles. This is a typical treatment for bus-only links allowing buses to make turns prohibited to general traffic. It has also been used for other bus-only link applications in communities where motorists generally respect traffic control devices.
- **Gates.** A variety of gates and movable barriers have been used internationally to allow bus access while preventing access by private vehicles. The gates open when an authorized vehicle is detected (e.g., using a transponder or a transmitter). Examples include parking lot–style gates, swinging gates, rolling gates, and descending bollards. The gates are supplemented with appropriate signs and pavement markings. These devices physically restrict access into or between selected areas to buses only, but maintenance can be an issue.
- **Automobile traps.** These are self-enforcing barriers that physically prevent automobile passage while permitting buses and other wider or higher vehicles (e.g., fire trucks) to pass through the link. Examples include pits in the roadway designed to trap automobile wheels and raised blocks that catch the undercarriage of an automobile. Similar types of barriers were used as part of early traffic-calming programs in some U.S. cities to allow fire truck access between closed street segments while preventing through automobile traffic (Smith and Appleyard 1980). Traps have generally fallen out of favor as a traffic-calming treatment in the United States but continue to be used internationally for bus-only links.
- **Photo enforcement.** If local laws permit, photo or video enforcement is an option for enforcing bus-only links without resorting to gates or traps.

Bus-only links that provide access between neighborhoods or into activity centers typically have provisions for pedestrian and bicycle access as well.

Companion Strategies

Bus-only links can be used to provide more-direct bus routes within suburban areas (Section 5.3). One application is to allow buses to make turns prohibited for other vehicles (Section 6.1). Red-colored pavement (Section 7.4) is an option for highlighting roadway sections open only to buses. Enforcement measures (Section 6.13) are suggested for links that do not use physical means to prevent access by unauthorized vehicles.

Constraints

Installing bus-only links in established neighborhoods may raise neighborhood concerns about unauthorized usage, new routes into the neighborhood for criminals, or the potential to open the link to general traffic at some point in the future. While the use of gates is permitted by the MUTCD, descending bollards are not discussed and would likely require an experimentation request to the FHWA if proposed for a roadway open to public travel, while pit trap treatments would likely raise liability issues in a U.S. context. Raised "undercarriage preventers" will likely be ineffective with pickup trucks, sport-utility vehicles, and other higher-slung vehicles, and may block police or fire chief cars (Smith and Appleyard 1980).

Benefits

Bus-only links support more-direct bus routings, which can reduce the time required for a bus to travel a route or can expand the area served by a bus route within a given cycle time. In suburban areas, they may allow minimal bus service to be provided to areas that could not otherwise support bus service due to the out-of-direction travel required. They can also support neighborhood traffic management programs by preserving bus access while eliminating routes for cut-through traffic.

Other stakeholders that may be supportive of bus-only links are:

- Emergency responders (e.g., fire, police, ambulance), as these links help reduce response times; law enforcement may also see them as supportive of police activities (e.g., ability to surround a block to catch a suspect in hiding) (Smith and Appleyard 1980);
- School districts, which can plan more-direct school bus routes;
- Neighborhood residents, who are provided with new options for recreational walking and bicycling routes on low-volume streets; and
- Bicycle advocacy groups, if a proposed link offers an opportunity to expand a community's bicycle network.

Cost Considerations

- **Planning and coordination costs.** Low (when installed by policy as part of new subdivisions or when incorporated into a larger traffic management project) to moderate (when proposed for an existing neighborhood as a stand-alone project). For gate applications, coordination will be required with other authorized users to make sure their vehicles are equipped with a means of opening the gate (e.g., a transmitter).
- **Capital costs.** Low (signing and marking only) to moderate (other types of treatments).
- **Maintenance costs.** Gate applications are subject to mechanical failures and vandalism. Due to the need to maintain bus service, it is important to have staff available to immediately respond to gate failures, and it may be necessary to leave the gate open if it cannot be repaired immediately. Calgary experiences approximately one stuck vehicle per month at one of its pit trap–type links.
- **Bus operations costs.** Can significantly shorten bus routes in suburban areas, allowing the same bus route to serve adjacent neighborhoods. When used as part of a traffic management program, delays caused by other traffic may be reduced as a result of lower traffic volumes.
- **Other user costs.** Typically no impact (since no link was provided previously). When used as part of a traffic management program, it is the program itself that creates impacts to other users; the bus-only link serves to preserve access for buses.

Implementation Examples

Calgary, Canada, uses bus-only links to provide transit bus, paratransit vehicle, school bus, and emergency vehicle access between adjacent subdivisions that have no public street connection. Early links used a pit-type trap, supplemented by several warning signs, to prevent through-vehicle traffic. Some of these links have subsequently been retrofitted with parallel gate-controlled access points for use if a vehicle becomes stuck in the trap. Newer installations only use gates. As of 2014, Calgary had 10 gates in active use by transit (three pit-only, two pit-and-gate, and five gate-only). Two other pit-and-gate systems have been installed for future bus use and are currently used by emergency vehicles. Three other gates are designated in local development plans for future construction if needed for transit use (Calgary Transit, no date).

Ottawa, Canada, has installed bus-only left-turn lanes at key intersections where there is insufficient capacity to serve general left-turning traffic but it is desired to provide direct bus routings. Bus-only links are used to connect some neighborhoods that have limited street connectivity to allow bus routes to penetrate neighborhoods rather than go around them. These streets are controlled only by signs, but OC Transpo staff believe the violation rate is low.

Portland, Oregon, has installed bus-only left-turn lanes at a couple of locations. One site provides access to the 5th Avenue transit mall; the other site provides a direct routing for buses at a complex intersection where there is insufficient capacity to directly serve automobile left turns.

Other international examples include the Copenhagen, Denmark, region (at least 18 links); Sorø, Denmark; London, United Kingdom; and Delft and The Hague, Netherlands.

Implementation Guidance

The following considerations apply to bus-only links:

- Bus-only links can be considered when there is a need to provide transit service with the most direct routing possible without encouraging additional motorized vehicle traffic.
- Access should be provided to other public service users that would benefit from the link, such as emergency responders and school buses.
- The design of the link should clearly indicate to motorists that it is not for use by general traffic. Signs, pavement markings, entrance design, placement, and passive and active enforcement measures contribute to communicating this message.
- The entrances to a link are preferably placed at locations, such as intersections, where motorists can change their travel direction to avoid the link or can continue straight past the entrance. Midblock locations are more likely to experience violations as well as problems with vehicles blocking access to or from the link while making a three-point turn.
- Links are preferably designed to accommodate pedestrians and bicycles except when connecting to facilities where pedestrians and bicyclists are prohibited.
- Unless previous experience (for example, with neighborhood traffic calming) indicates a potential for violations, signing and marking could be adequate. However, the potential for enforcement should be planned for and integrated into the design if the need arises.
- In the United States, parking lot–style gates and sliding gates are the most feasible options for physically restricting access to authorized vehicles. Ongoing maintenance needs should be considered during planning, and an operations plan should be developed for addressing situations when a gate will not open or is blocked.
- Trap-type treatments, whether raised or lowered, are not suggested for U.S. applications due to a lack of support for them in U.S. design standards.

Additional Resources

- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—Section 2B.68 addresses the use of gates on public roadways.
- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.5.7.1 discusses bus-only links, while Section 5.5.7.3 discusses bus-only turn lanes. It recommends that "normal practice" should be used in the design of the link, and the signs should clearly indicate that the link is for authorized vehicles only. If there is a risk of a high violation rate, the guide suggests (1) additional and larger signs, (2) traffic signal control, (3) physically gating the roadway, or (4) photo or video enforcement.
- *TCRP Web-Only Document 66: Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies*—Appendix E presents the results of an international literature review on bus-only links.

CHAPTER 8

Bus Lane Toolbox

This final toolbox chapter presents a variety of available bus lane strategies. Considerations applicable to all (or most) types of bus lanes are presented first, followed by shorter sections specific to individual types of bus lanes that discuss what sets them apart from other types of bus lanes.

Chapter 8 discusses the following strategies:

- Bus lanes (generally),
- Curbside bus lanes,
- Shared bus and bicycle lanes,
- Offset bus lanes,
- Left-side bus lanes,
- Queue bypasses,
- Two-way median bus lanes,
- Contraflow bus lanes, and
- Two-way, single-lane bus lanes.

The introduction to Chapter 5 describes how each strategy section is organized.

8.1 Bus Lanes (Generally)

Description

A roadway lane dedicated exclusively or primarily to the use of buses.

Purpose

To reduce the delay that occurs when buses must share a lane with other traffic. Bus lanes allow buses to avoid traffic delays when waiting for a gap when exiting bus stops, to bypass queues of through-vehicles stopped at a traffic signal, and (with some types of lanes) to avoid the delay caused by turning vehicles—benefits that would otherwise require a package of individual transit-supportive roadway strategies.

Applications

Bus lanes are typically considered in the following situations:

- On urban streets with relatively high bus and general traffic volumes, where many buses and their passengers are subject to delay;

- In corridors with BRT or other premium bus service, where maximizing bus speeds and reliability is a priority; and
- On shorter stretches of roadway, allowing buses to bypass a bottleneck or to move to the front of a queue (Kittelson & Associates et al. 2013).

Bus lanes may operate full time or during designated hours only. Depending on the available right-of-way and its current use, they can be created by eliminating curbside parking, by converting an existing travel lane to bus-only use, by using available space in the roadway median, by widening the roadway, or a combination of these. They may be dedicated to bus use only, they may allow designated vehicles (e.g., taxis, bicycles) to share the lane, or they may allow other vehicles to enter the lane to make right turns or pick up and drop off passengers.

Companion Strategies

Any of the bus operations strategies described in Chapter 5 are potentially applicable to bus lanes. Prohibiting right turns by general traffic (Section 6.2) results in better bus lane operations (as buses avoid waiting behind right-turning vehicles queued at a red light or waiting for pedestrians to clear the crosswalk) and gives transit agencies considerable flexibility in where bus stops are located (Section 5.1).

Passive traffic signal timing adjustments (Section 6.4) can be considered with any bus lane application; when bus volumes are relatively high (e.g., a bus arrival every other traffic signal cycle or more frequently), timing signals to allow buses to progress in the peak direction of travel may be appropriate. With lower bus volumes, where priority would not be requested nearly every traffic signal cycle, transit signal priority (Section 6.7) is an option. Bus-only signal phases (Section 6.9) may be required to serve bus turning movements that would conflict with through traffic if made from the bus lane. Pre-signals (Section 6.11) are an option for providing a virtual bus lane beyond the point where constraints make it infeasible to continue a physical bus lane. Bus lanes will usually require some degree of enforcement (Section 6.13) to realize their full benefit.

It may be beneficial to shift routes serving parallel streets onto the street with a bus lane to use the lane more efficiently; in these cases, bus stops may need to be lengthened (Section 7.2) to accommodate the increased bus volumes. Red-colored pavement (Section 7.4) improves the conspicuity of bus lanes, which helps reduce inadvertent violations of the bus lane by other vehicles.

Constraints

Potential constraints depend on how the bus lane would be developed and are discussed in detail in the sections of this chapter that describe specific bus lane types. For example, when developing curbside bus lanes (Section 8.2) by removing on-street parking and delivery zones, the needs of adjacent land users that currently rely on those uses of the curb space will need to be considered. When developing interior bus lanes (Section 8.4) by converting a general traffic lane to bus use, it is mainly how the roadway will operate for general traffic with a reduced number of lanes that will need to be considered (although whether some traffic would divert to parallel routes may need to be taken into account). When developing bus lanes in the median of a roadway, whether sufficient space is available for both the bus lanes and bus stops will need to be considered, as will potential issues with removing existing landscaping.

Benefits

Bus lanes can improve bus travel times and bus travel time variability. The magnitude of the improvement depends on a number of factors, including the ability of buses to avoid delays from right-turning traffic, illegal stopping and parking activity in the lanes by other vehicles, and the level of congestion that existed on the roadway prior to the development of the bus lanes. The *Transit Capacity and Quality of Service Manual*'s procedure for estimating bus speeds estimates that bus lanes in a central business district (CBD) save buses an average 1.8 min per mile relative to mixed traffic operations when right turns are not allowed from the bus lane. When right turns are allowed, buses save an average 1.0 min per mile, and when bus lanes are regularly blocked by illegally parked and stopped vehicles, buses save an average of 0.0 to 0.5 min per mile. In non-CBD environments, bus lanes save buses an average 0.3 min per mile relative to mixed traffic (Kittelson & Associates et al. 2013, derived from St. Jacques and Levinson 2000).

Examples of actual bus lane experience summarized in *TCRP Report 118: Bus Rapid Transit Practitioner's Guide* found travel time savings of 0.1 to 1.5 min per mile in Los Angeles and Dallas when expressed as a travel time rate, and savings of 34% to 43% in New York and San Francisco when expressed as a percentage. In addition, travel time variability as measured by the coefficient of variation of travel times (the standard deviation of travel time divided by the average travel time) was reduced by 12% to 57% in Los Angeles and New York (Kittelson & Associates et al. 2007).

Cost Considerations

- **Planning and coordination costs.** High. Since bus lane projects are implemented over relatively long lengths of roadway in comparison to the intersection focus of most other types of infrastructure strategies, stakeholder engagement, traffic analysis, and similar efforts will need to address a corresponding large area.
- **Capital costs.** Low to high, with a large range of potential costs, ranging from installing new striping and pole-mounted signing (low), to providing overhead signing (moderate for each installation), to widening the roadway or reconstructing the roadway median (high).
- **Maintenance costs.** Relatively low if the bus lane is created by restriping an existing lane, in which case there may be some added costs to maintain the striping and new signs. If the bus lane is created by widening the roadway or creating a new facility in the roadway median, then the costs will be high relative to other strategies due to the new pavement area requiring maintenance.
- **Bus operations costs.** Bus lanes are typically implemented to provide a significant time savings for buses and can produce equally significant cost savings when used by high-frequency routes. Note that there is a difference between one route operating on a bus lane at high frequency versus several low-frequency routes that combine to provide a high frequency. The former situation is more likely to result in sufficient time savings to save a bus, although as discussed in Appendix B, lesser time savings can still provide benefits to transit agencies and their passengers. Bus lanes typically require some degree of enforcement to operate effectively, which entails added operating costs (see Section 6.13).
- **Other user costs.** These costs depend on the type of bus lane developed; see the following sections on specific bus lane types for details.

Implementation Examples

See the sections of this chapter describing specific bus lane types for implementation examples.

Implementation Guidance

In any bus lane evaluation involving converting a lane to bus use, it is important to consider whether some existing traffic might choose to use a parallel route in the future, thus reducing the overall impact to roadway operations. If a jurisdiction's experience is that motorists choose alternate routes when long-term road construction projects occur that close traffic lanes, the same will likely occur when a general traffic lane is converted to a bus lane.

Full-Time Versus Part-Time Lanes

Full-time lanes are easier to practice enforcement on and continue to provide a travel time reliability benefit during hours when general traffic volumes are lower and the bus lane does not provide as much of a travel time benefit relative to mixed-traffic operations. Part-time lanes allow other roadway users to access the lanes at times when bus and general traffic volumes are lower and are often used in conjunction with curbside lanes where the curb space is desired to be used for deliveries and off-street parking during off-peak hours. However, particularly when the curb is used for parking during off-peak hours, regular enforcement (e.g., daily tow truck sweeps) will be needed to ensure that the lane is available for buses when it is most needed. Median bus lanes (Section 8.7) and single-lane reversible bus lanes (Section 8.9) are typically operated as full-time bus lanes.

Right-Turn Prohibitions

As indicated in the Benefits section, bus lanes lose nearly half of their travel time savings benefit in CBD areas when right-turning traffic is allowed to enter the bus lane prior to intersections. The right-turning traffic frequently has to yield to pedestrians, and these vehicles block the bus lane while waiting for the crosswalk to clear. Nevertheless, it may be impractical to prohibit right turns along the entire length of the bus lane. Options for addressing right turns include:

- Providing right-turn lanes to the right of an interior bus lane, for example by using the width taken by the curbside parking lane and adjusting lane widths as needed on the intersection approach.
- In CBD areas, prohibiting right turns at minor intersections so as to concentrate right turns at other intersections, where they can be addressed by other transit-supportive strategies.
- In suburban areas, implementing access management strategies that reduce the number of access points between intersections.
- In areas with a one-way street grid, locating bus stops at intersections where one-way traffic approaches from the right and right turns would be prohibited anyway.
- Ending the physical bus lane and creating a virtual bus lane through the use of a queue jump at the previous traffic signal (Section 6.10) or a pre-signal in advance of the intersection (Section 6.11) that allows buses to enter the general traffic lane ahead of other traffic.

Shared Use

In situations where the number of buses proposed to use the lanes initially is relatively low (even after rerouting other bus routes to the new facility), and the policy environment is less supportive of transit, it may be necessary to make compromises on how the bus lane is used in order to get something implemented. One potential compromise is to allow other authorized users (e.g., non-transit buses, taxis, bicycles) to use the lane to give it a greater appearance of being used and to build support for the bus lanes with other stakeholder groups that would benefit.

Visibility

Measures that increase the visibility of a bus lane can help reduce the number of inadvertent bus lane violations and make the lane easier to enforce, thus allowing the lane's travel time and reliability benefits to be maximized. These measures include red-colored pavement (Section 7.4) and overhead signage such as that illustrated in the photograph at the beginning of this section.

Additional Resources

The following resources provide guidance applicable to bus lanes in general. Where applicable, the other sections in this chapter list additional resources applying to a specific bus lane type.

- *Manual on Uniform Traffic Control Devices* (FHWA 2009)—Chapter 2G discusses bus lane signs as part of a broader presentation of preferential and managed lane signs. Chapter 3D presents pavement markings for preferential lanes, including bus lanes.
- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014)—Section 5.4.1.1 provides guidance on justifying the need for bus priority treatments, including bus lanes. Section 5.5 provides design guidance for many types of bus lane, while Section 5.6 provides design guidance for median busways and bus streets. Section 5.7 discusses enforcement needs specific to bus lanes.
- *Designing Bus Rapid Transit Running Ways* (APTA 2010)—this APTA recommended practice provides guidance on selecting and designing an appropriate bus lane type to support BRT.
- *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition (Kittelson & Associates et al. 2013)—Chapter 6 provides analytical methods for estimating bus speeds on bus lanes.
- *TCRP Report 118: Bus Rapid Transit Practitioner's Guide* (Kittelson & Associates et al. 2007)—Chapter 4 provides general cost information (as of 2004) for different bus lane types as well as cost information specific to individual BRT routes in operation at the time of writing.
- *TCRP Report 90: Bus Rapid Transit, Volume 1: Case Studies in Bus Rapid Transit* (Levinson et al. 2003)—this report provides 26 case study examples of cities with BRT routes in operation at the time of writing, most of which used some sort of bus lane as part of the overall BRT package.

8.2 Curbside Bus Lane

Description

A bus lane located in the rightmost lane of the roadway and adjacent to the right curb.

Purpose

To provide basic bus lane benefits without needing extensive capital improvements beyond signing and pavement markings.

Applications

A typical application is to convert a curbside parking lane to bus-only use on a full- or part-time basis, allowing a bus lane to be developed without removing a general traffic lane. Dual bus lanes, which can be necessary when very high bus volumes (e.g., 100 or more buses per hour) must be served, are a variation of curbside bus lanes.

Companion Strategies

See the list of generally applicable companion strategies in Section 8.1. Enforcement (Section 6.13) is a particularly important consideration for curbside bus lanes due to their potential use for unauthorized parking, deliveries, and passenger pickups and drop-offs, particularly when the lanes convert to parking during off-peak hours. Queue jumps (Section 6.10) and pre-signals (Section 6.11) are options for creating a virtual bus lane when a physical curbside bus lane needs to end due to downstream constraints on the use of the curb space. Shared curbside bus and bicycle lanes are covered in Section 8.3.

Constraints

A key constraint is the potentially large number of competing users that also have a stake in how the curb space is used. Competing uses include bus stops, right-turning traffic, parking, deliveries, passenger pickup and drop-off, taxi stands, bicycles, service and maintenance vehicles, and usage as a temporary sidewalk when an adjacent building is under construction (AASHTO 2014). Some of these competing uses may be able to be accommodated from other locations—for example, on the opposite side of the street, on side streets, or off the street (AASHTO 2014).

Benefits

See the general bus lane discussion in Section 8.1. Because of the interference caused by right-turning traffic stopped for pedestrians in crosswalks, curbside bus lanes will produce smaller benefits for buses than other bus lane types when right turns need to be accommodated at intersections. There will also typically be some degree of illegal driving, parking, or stopping activity in the lane despite active enforcement efforts.

Cost Considerations

See the general bus lane discussion in Section 8.1. When created by converting an existing lane, curbside bus lanes will generally have lower capital costs than other bus lane types since only signing and pavement marking changes will be needed.

Implementation Examples

Curbside bus lanes have been implemented in many North American cities, including Columbus, Ohio; Denver, Colorado; Edmonton, Canada; Eugene, Oregon; Las Vegas, Nevada; Miami, Florida; Minneapolis, Minnesota; New Orleans, Louisiana; New York, New York; Ottawa, Canada; Portland, Oregon; Richmond, Virginia; San Antonio, Texas; San Francisco, California; Seattle, Washington; and Spokane, Washington (Danaher 2010, St. Jacques and Levinson 2000).

Implementation Guidance

The general bus lane discussion in Section 8.1 is particularly applicable to curbside bus lanes since these lanes are most susceptible to pressure to allow other road users at specific times or places.

Additional Resources

Section 5.5.2 of the *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014) provides design guidance for curbside bus lanes. See also the resources generally applicable to bus lanes in Section 8.1.

8.3 Shared Bus and Bicycle Lane

Description

A curbside lane shared part- or full-time by buses and bicycles; other users may also be allowed into the lane at specific times or locations.

Purpose

To reduce the impact of general traffic on both buses and bicycles when insufficient roadway space is available to provide separate exclusive facilities for the two modes.

Applications

Shared bus and bicycle lanes have been used where it was desired to assist both bus and bicycle traffic, but right-of-way constraints prevented developing separate bus and bicycle facilities. Buses travel more quickly than in a mixed-traffic environment, while bicyclists are provided with some separation from general traffic (Hillsman et al. 2012). Allowing bicyclists to use the bus lane (1) may generate broader support for developing a bus lane by increasing the number of stakeholders that benefit from the lanes and (2) may, particularly when bus service is relatively infrequent, help reduce the perception that the lane is not being used efficiently.

Hillsman et al. (2012) categorized shared bus and bicycle lanes as follows: (1) short segments generally less than 0.5 mile long that have constrained right-of-way (e.g., bridges) and serve to connect or extend bicycle facilities, (2) urban segments that are generally less than 2 miles long and are typically located on key commuter routes to downtowns, and (3) suburban/low-density segments that are generally more than 2 miles long and are typically located on high-volume arterial roadways.

Companion Strategies

See the list of generally applicable companion strategies in Section 8.1. Some of the traffic signal–related strategies given in Chapter 6 can be used at the same time to benefit bicycles, including transit signal priority (Section 6.7), bus-only signal phases that do not conflict with parallel bicycle traffic (Section 6.9), queue jumps (Section 6.10), and pre-signals (Section 6.11). Bus-specific signals (Section 6.12) could also benefit bicycle turning movements, particularly when a well-used bicycle route follows the same alignment as the bus route. Bicycle signal heads can be considered to control bicycle movements when bicycle priority will be given in conjunction with bus priority. At the time of writing, bicycle signal heads were permitted by FHWA Interim Approval IA-16 (Lindley 2013), with the condition that jurisdictions submit a written request to FHWA to use them. They are expected to be included in the next edition of the MUTCD.

Constraints

Roadways with significant uphill grades are not good candidates for relatively narrow shared lanes because the speed differential between bicycles and buses is considerably greater compared to level or downhill roadway sections, and buses would experience greater delay in situations where they could not immediately pass bicyclists. Roadways with a high volume of traffic in the adjacent lane are also not good candidates for relatively narrow shared lanes since buses would frequently have to slow behind bicyclists while waiting for a gap in traffic to move around the bicyclist, and because bicyclists would need to pass stopped buses in the travel lane unless it is possible to route bicycles around bus stops.

Benefits

See the general bus lane discussion in Section 8.1. Similar to curbside bus lanes, shared bus and bicycle lanes will not provide the same level of benefit as other bus lane types, particularly when right turns need to be accommodated at intersections, and there will typically be some degree of illegal driving, parking, or stopping activity in the lane despite active enforcement efforts. In addition, when the shared lane is too narrow for buses to go around bicycles without encroaching on the adjacent lane, buses may experience a delay waiting for a suitable gap in traffic to pass the bicyclist or while traveling at the speed of the bicyclist.

Cost Considerations

See the general bus lane discussion in Section 8.1. Shared bus and bicycle lanes will have slightly higher costs than curbside bus lanes due to the extra signs and pavement markings required specific to bicycles.

Implementation Examples

Hillsman et al. (2012) identified 27 roadways where shared bus and bicycle lanes were being used in the United States as of 2012, plus additional examples of lanes that were being proposed at the time of the research or that had been removed. They also identified examples internationally in Vienna, Austria; Ghent, Belgium; Ottawa, Toronto, and Vancouver, Canada; Paris, France; Geneva, Switzerland; and Edinburgh and London, United Kingdom.

Implementation Guidance

Applications

NACTO (2012) indicates that bicycle lanes "are most helpful" (1) when the speed limit is at least 25 mph, (2) on streets with large numbers of buses, and (3) on streets where the motorized vehicle average daily traffic is 3,000 vehicles or more. Based on this guidance, bicycle lanes or other dedicated bicycle facilities would be preferred in most situations where a bus lane might be considered and bicycle traffic needs to be accommodated. Situations where a shared lane might be considered are (1) business districts with speed limits of 20 mph, (2) bus lanes that would be used by a low volume of buses and a low-to-moderate volume of bicycles (to improve perceptions that the lane is being used), and (3) locations with insufficient right-of-way to accommodate bus and bicycle traffic in separate facilities. In the latter case, short sections of shared lane without bus stops would operate better for both buses and bicycles compared to frequently spaced stops across longer sections, unless it is possible to route bicycles around bus stops.

Shared-Lane Width

A 16-ft lane width allows buses to pass bicycles without encroaching into the adjacent lane (but might encourage right-turning vehicles, if allowed in the lane, to pull in front of stopped buses), while a 14.5-ft width allows bicycles to pass buses without encroaching into the adjacent lane. However, widths down to 11 ft (i.e., the minimum recommended bus lane width in AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets* [2014]) still provide better separation between bicycles and general traffic than occurs in a mixed-traffic environment and may be appropriate in situations where bus volumes are relatively low (e.g., less than one every other traffic signal cycle on average) or in downtown environments where blocks are short and buses travel relatively slowly and are unlikely to pass bicyclists. When more than 16 ft of width is available, consider providing separate bus and bicycle facilities unless local standards specify greater minimum bus or bicycle widths (e.g., 12 and 5 ft, respectively). Wider lanes tend to promote side-by-side automobile driving, increased heavy vehicle use, and higher motor vehicle speeds (AASHTO 2014).

Other Considerations

Transit staff in Ottawa interviewed for TCRP Project A-39 believed that while shared bus and bicycle lanes are not an ideal solution, they are safer than the before condition where buses, trucks, automobiles, and bicycles would compete for the same space. Shared bus and bicycle lane implementations in Ottawa have experienced increased bicycle volumes, indicating that bicyclists preferred them to the mixed-traffic situation.

Some concern has been raised about the potential for buses and bicycles to leapfrog each other in shared lanes since they often travel at similar average speeds in urban environments (Hillsman et al. 2012; AASHTO 2014). A study of the operation of shared bus and bicycle lanes did not find support for the leapfrogging effect except perhaps on one higher-speed roadway that was studied. However, more research is required (Hillsman et al. 2012). Appendix C provides guidance on managing bus and bicycle conflicts at bus stops.

See also the general bus lane discussion in Section 8.1.

Additional Resources

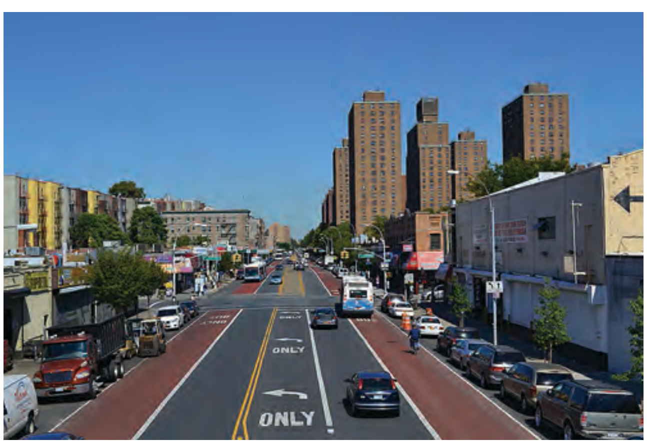
In addition to the generally applicable bus lane references presented in Section 8.1, and Appendix C: Managing Bus and Bicycle Interactions, which includes a literature review on shared bus and bicycle lanes and guidance on developing them, the following resource provides information specific to shared bus and bicycle lanes:

- *A Summary of Design, Policies and Operational Characteristics for Shared Bicycle/Bus Lanes* (Hillsman et al. 2012)—a review of the design and operation of the shared bus and bicycle lanes known to exist in the United States at the time of writing.

8.4 Interior (Offset) Bus Lane

Description

A bus lane in the interior of the roadway that is typically located to the left of the curb (parking) lane but can also be in another non-curb lane.



Purpose

Interior bus lanes are typically used to preserve curb space for on-street parking, deliveries, and other uses while providing a space in the roadway that provides priority to buses.

Applications

Interior bus lanes are potentially applicable when curb space is desired to be preserved for other uses or right-turning traffic is sufficiently high to make separate right-turn lanes desirable. Both situations are common in urban areas; right-turning delays can also be an issue in suburban commercial strips (AASHTO 2014).

An interior bus lane is created by converting a travel lane to a bus lane; it thus affects the roadway's capacity. AASHTO (2014) recommends having at least two other travel lanes available in the same direction of travel, which would suggest that interior bus lanes would only be an option for six-lane or wider arterial streets and one-way streets with three or more existing travel lanes. However, New York City has had success implementing interior bus lanes on five-lane roadways such as Webster Avenue by maintaining left-turn lanes where needed and allowing right turns to be made from the bus lane at low-volume intersections and from separate right-turn lanes at higher-volume intersections (New York City DOT and MTA-NYCT 2014). At the time of writing, New York City was also considering creating an interior bus lane in the second lane from the curb to allow dual right-turn lanes to be developed at a downstream intersection (New York City DOT 2014).

Companion Strategies

See the list of generally applicable companion strategies in Section 8.1. Interior bus lanes work well in combination with curb extensions (Section 7.5), which can also help increase the amount of available on-street parking since parking does not need to be removed before or after a stop to give buses access to a curbside stop. Traffic control strategies such as left-turn restrictions (Section 6.2) at key intersections can help improve traffic flow in the remaining general-purpose lanes.

Constraints

The main potential constraint for interior bus lanes is the loss of roadway capacity; thus, this is primarily a strategy to be considered in locations where policy environments permit some degradation of roadway operations. New York City has experienced success with a combination of traffic control strategies (e.g., turn restrictions and other traffic pattern changes) at busy intersections and using short sections of curbside bus lanes to provide two through lanes or dual turn lanes where needed to serve traffic operations requirements (New York City DOT and MTA-NYCT 2014).

Benefits

See the general bus lane discussion in Section 8.1. Interior bus lanes provide the option for using the curb lane as a right-turn lane at intersections (with any bus stop located on a far-side curb extension), which provides more flexibility for accommodating right turns without significantly affecting bus operations. Thus, interior bus lanes with curb-lane right-turn lanes will operate similarly to curbside bus lanes that prohibit right turns in terms of the impact of turning traffic on buses. Buses traveling in interior bus lanes may experience brief delays associated with vehicle parking maneuvers that buses in curbside bus lanes would not experience, but they are less likely to experience the need to leave the lane to go around vehicles illegally stopped in the lane. General traffic flow benefits from interior bus lanes because parking movements occur from the bus lane rather than a general traffic lane, resulting in smoother general traffic flow between intersections.

Cost Considerations

See the general bus lane discussion in Section 8.1. Interior bus lanes may require higher capital and maintenance costs than curbside bus lanes due to the potential need for overhead signs to make the bus lane more visible to motorists.

Implementation Examples

Interior bus lanes are New York City's preferred bus lane strategy for its SBS routes. They have also been used in Ottawa, Canada (AASHTO 2014).

Implementation Guidance

See the general bus lane discussion in Section 8.1. Implementing interior bus lanes on relatively narrow (e.g., four- or five-lane two-way roadways) will likely require a combination of creative transit and traffic engineering strategies. As a result, this strategy is one where it is essential that transit and roadway agency staff work closely together to develop mutually satisfactory solutions.

Additional Resources

See the general bus lane discussion in Section 8.1 as well as Section 5.5.3 of the *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014). In addition, New York City DOT and MTA-NYCT have performed a series of follow-up studies on their SBS routes, most of which include sections with interior bus lanes. These reports are available on New York City DOT's Bus Rapid Transit website, http://www.nyc.gov/html/brt/html/routes/routes.shtml.

8.5 Left-Side Bus Lane

Description

A bus lane on the left side of the roadway that is adjacent to the left curb on one-way streets or adjacent to the median on two-way streets.

Purpose

Left-side bus lanes are typically applied in special-purpose situations where a more conventional location is infeasible.

Applications

Examples of situations where left-side bus lanes have been used are:

- Where attempting to avoid traffic congestion in the right-hand lanes,
- In preparation for a downstream left turn, and
- Commuter bus routes that operate express (i.e., without stops) for long stretches.

Companion Strategies

See the list of generally applicable companion strategies in Section 8.1. Median bus lanes (Section 8.7) are a related strategy. If bus stops are to be provided along a left-side bus lane, either boarding islands (Section 7.6) or a bus equipped with doors on both sides (Section 5.5) will be required.

Constraints

Depending on how the bus lane is developed—by taking parking from the left curb or by converting a general traffic lane to bus use—the same constraints faced by curbside bus lanes

(Section 8.2) or interior bus lanes (Section 8.4), respectively, will apply. When conventional buses will be serving bus stops along a left-side bus lane, sufficient roadway space needs to be available to provide an ADA-compliant boarding island.

Benefits

See the general bus lane discussion in Section 8.1. Left-side bus lanes avoid right-turning traffic interferences that can be encountered with more conventional bus lanes. Typically, left turns are prohibited from left-side bus lanes, or left-turning traffic is allowed to cross the bus lane into a left-turn bay; therefore, buses do not experience significant interference with left-turning traffic.

Cost Considerations

See the general bus lane discussion in Section 8.1. Left-side bus lanes will experience slightly higher capital and maintenance costs than curbside bus lanes due to the need for signs to inform motorists on side streets about the presence of the left-side lane.

Implementation Examples

Left-side bus lanes are provided on several street segments in San Francisco, including portions of Bush Street, Folsom Street, Fremont Street, and Beale Street. Mirabdal and Thesen (2002) describe the operation of another left-side bus lane in San Francisco. Left-side bus lanes with boarding islands are found in Paris, and left-side bus lanes served by buses with doors on both sides are found in the Public Square area in downtown Cleveland, Ohio (AASHTO 2014) and on the one-way couplet portion of Pioneer Parkway in Springfield, Oregon.

Implementation Guidance

Motorists turning onto a street with a left-side bus lane will likely need special signs to indicate which lane(s) they should turn into (AASHTO 2014). See also the general bus lane discussion in Section 8.1.

Additional Resources

Section 5.5.5 of the *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014) provides design guidance for left-side bus lanes. See also the resources generally applicable to bus lanes in Section 8.1.

8.6 Queue Bypass

Description

A relatively short bus lane that allows buses to move to the front of the line at a bottleneck, where they then merge into the adjacent general traffic lane.

Purpose

To avoid delays caused by waiting in the general traffic queue to pass the bottleneck.

Applications

Queue bypasses are potentially applicable anywhere a traffic bottleneck is created intentionally (e.g., freeway ramp meters, toll plazas) or as a result of constrained right-of-way that reduces roadway capacity (e.g., where two lanes merge into one prior to a narrow bridge or underpass). Queue jumps can also be applied on a temporary basis to maintain bus travel times through work zones where roadway capacity is temporarily reduced (AASHTO 2014). Although it is possible to locate a bus stop along a queue bypass, they are more commonly used on sections of a route where buses do not stop.

Companion Strategies

Queue jumps (Section 6.10) and pre-signals (Section 6.11) are related strategies, but these rely on traffic signal control to merge buses into the general traffic lane. Shoulder use (Section 7.3) is another related strategy. See also the general bus lane discussion in Section 8.1.

Constraints

When the bottleneck is created intentionally, such as at a ramp meter, there needs to be sufficient right-of-way available to provide a bypass lane long enough for buses to avoid the queue in most circumstances. When the bottleneck is created by a roadway capacity constraint, it might be possible to take a general traffic lane to create the queue bypass lane since this has the effect of moving the general traffic merge point upstream but typically does not affect general traffic delay (the time spent waiting in the queue simply occurs at a different point on the roadway). However, as the back of the queue also moves upstream, there needs to be sufficient space to store the queue without it spilling back into upstream intersections.

Benefits

The magnitude of the benefit depends on how much delay general traffic experiences at a bottleneck, which in turn depends on the degree to which roadway demand exceeds capacity. The benefit might be a time savings on the order of 1 min at a freeway ramp meter to 10 min or more in the case of a severe capacity constraint on an arterial roadway. Travel time variability would also be expected to improve.

Cost Considerations

See the general bus lane discussion in Section 8.1. The overall project cost will often be lower than for other kinds of bus lanes because queue bypass projects tend to be shorter, but the cost will be similar to other types of bus lanes when calculated on a per-mile basis. Capital and maintenance costs will depend on whether new pavement is required to create the lane or whether an existing lane is converted to bus use only.

Implementation Examples

Many examples exist of ramp-meter queue bypasses to serve bus routes entering freeways from surface streets. The bus/high-occupancy vehicle bypass lanes at the San Francisco Bay Bridge toll plaza in Oakland, California, is an example of bypass lanes that can save buses many tens of minutes during peak periods. Arterial queue bypasses in North America are not well-documented (and finding them is complicated by the fact that the terms *queue jump* and *queue bypass* are often used interchangeably), but international literature (e.g., U.K. Department for Transport 2004, Public Transport Authority of Western Australia 2011) includes examples of queue bypasses being used on approaches to narrow bridges and underpasses and in congested city centers.

Implementation Guidance

See the general bus lane discussion in Section 8.1. The main implementation criterion is that the queue bypass lane should start before the point that buses reach the back of the general traffic queue to allow buses to proceed without delay.

Additional Resources

See the general bus lane discussion in Section 8.1.

8.7 Median Bus Lane

Description

Lanes reserved for the exclusive use of buses. These lanes are located in the middle of a roadway and are often separated from other traffic by curbs or landscaped islands.

Purpose

To provide buses with an exclusive running way within a roadway, free from other traffic interference, except at signalized intersections.

Applications

Median bus lanes are typically used on BRT routes where the highest possible bus speeds and travel time reliability are desired. Similar to median-running light rail transit, they also help improve the visibility of transit service and the priority given to it.

Companion Strategies

Turning movements from a median bus lane at a signalized intersection will definitely require a bus-only signal phase (Section 6.9), and through movements will often require one, depending on how general traffic left turns are accommodated. See also the generally applicable companion strategies described in Section 8.1.

Constraints

After cost, the primary constraint to be addressed is the availability of right-of-way to accommodate both median bus lanes and stations along the bus lanes. Depending on the degree of separation of the bus lanes from other traffic and the need to accommodate bus turns from the bus lanes, median bus lanes typically require three to four lanes of width (AASHTO 2014). In addition, a sufficient number of through and turning general traffic lanes need to be maintained at intersections, and width may also be required for bicycle facilities, on-street parking, or other design features. The constraints associated with bus-only signal phases (Section 6.9) will also be applicable.

Benefits

Median bus lanes remove the primary sources of traffic interference (e.g., right-turning traffic, parking, delivery activity) that other types of bus lanes can experience. When physically separated from general traffic by curbs or islands, the potential for unauthorized use is very low except for the possibility of vehicles accidentally turning left into the bus lanes at a signalized intersection. As a result, median bus lanes promote good bus travel time reliability and remove most potential sources of bus delay other than traffic signal delays. One potential minus of median bus lanes with respect to bus delay is the need to accommodate general traffic left turns. This in turn may reduce the amount of green time available for bus movements compared to bus operations in a curbside or interior bus lane, resulting in more bus delay waiting for a "go" signal indication. The degree to which bus signal delay is increased will depend on a combination of the traffic signal timing and phasing, the bus stop location at the intersection, and the location of the left-turn lane relative to the bus lanes; it is best determined through simulation.

Cost Considerations

See the general bus lane discussion in Section 8.1. Median bus lanes are typically the most expensive bus lane option due to the extensive street reconstruction required to adequately separate the bus facility from general traffic and the need to provide stations and pedestrian access to those stations within the street median.

Implementation Examples

- **Cleveland, Ohio.** The Health Line BRT route operates in median bus lanes on Euclid Avenue. It uses buses with doors on both sides that can serve island platforms between the bus lanes or side platforms to the right of the bus lanes.
- **Eugene and Springfield, Oregon.** The EmX BRT service operates in median bus lanes on a portion of Franklin Boulevard in Eugene and Pioneer Parkway in Springfield. It uses buses with doors on both sides that serve both island and side platforms.
- **Richmond, British Columbia.** The former 98 B-Line BRT route from Vancouver to Richmond operated in median bus lanes on No. 3 Highway. The bus lanes were removed around 2009 when the elevated Canada Line rail line was constructed in the same corridor.
- **South America.** Many South American BRT systems feature extensive use of median busways (Levinson et al. 2003).
- **Malmö, Sweden.** The Malmöexpressen BRT line that opened in 2014 features median bus lanes constructed in a constricted right-of-way environment in the central portion of Sweden's third-largest city (Wedeby et al. 2014).

Implementation Guidance

AASHTO provides extensive design guidance on median bus lanes. Some key considerations are:

- **Degree of separation from traffic.** The more difficult it is for other traffic to access the bus lanes, the better the resulting bus operations will be. At the same time, other considerations, such as available street width, the need to accommodate emergency vehicles, and snowplowing operations may require a reduced level of separation. In order of increasing effectiveness, potential types of separation are lane markings, rumble strips, raised half-globes, raised mountable curbs, flexible posts, concrete barriers, and raised median islands (AASHTO 2014).
- **Station locations.** In a constrained right-of-way, locating stations on the far side of intersections allows a station, two bus lanes, and a general traffic left-turn lane to be provided within a consistent right-of-way envelope (i.e., without shifting the bus lanes from side to side). Options in

an even more constrained right-of-way include midblock stations served by signalized pedestrian crossings, island platforms served by buses with doors on both sides, and prohibiting left turns. Station platforms need to provide sufficient width to meet ADA requirements and to provide sufficient waiting and circulation space for passengers.

- **General traffic left-turn accommodations.** A common option is to provide a left-turn lane to the right of the bus lane at signalized intersections and to provide individual signal phases for general through traffic, general left-turning traffic, and buses. Buses receive less green time than through traffic under this arrangement. For one midblock BRT station in Malmö, Sweden, a queue jump in conjunction with a signalized pedestrian crossing was planned to allow the bus lane to cross the left-turn lane entrance without conflict. In this arrangement, the left-turn lane would be to the left of the bus lane at the downstream intersection, and buses could move at the same time as parallel through traffic. Another option is to prohibit left turns (e.g., forcing traffic to turn left at another less-constrained intersection or to make three rights). Allowing traffic into the bus lane to make left turns "is generally undesirable" (AASHTO 2014).
- **Bus turning accommodations.** The implementation guidance for bus-only signal phases (Section 6.9) includes guidance specific to median bus lanes.
- **Pedestrian access and crossing movements.** Pedestrian access to stations (including the need for accessible pedestrian signals) and the potential need to accommodate midblock pedestrian crossings will need to be addressed as part of the median bus lane design. The potential for illegal pedestrian crossing activity and the possible need for countermeasures will also need to be considered (AASHTO 2014).

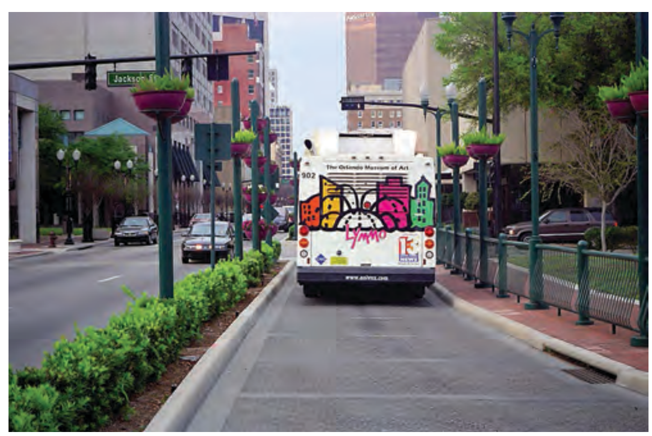
Additional Resources

Section 5.6 of the *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014) provides design guidance for median bus lanes. *TCRP Report 117: Design, Operation, and Safety of At-Grade Crossings of Exclusive Busways* (Eccles et al. 2007) provides guidance on providing pedestrian access to median bus lanes. See also the resources generally applicable to bus lanes in Section 8.1.

8.8 Contraflow Bus Lane

Description

A bus lane provided in the opposite direction of normal traffic flow on a one-way or divided street.



Purpose

To provide buses with a more direct routing through a one-way street grid, to keep both directions of a route on the same street, to take advantage of available capacity in the opposite direction of travel, or a combination of these.

Applications

Typical applications of contraflow bus lanes are:

- One-block sections of bus lane that allow a bus to conveniently reverse direction at the end of its route;
- Longer sections of bus lane that allow bus service to be provided in both directions on a one-way street, to retain existing two-directional bus service when a street is converted to one-way

operation, to reduce the number of turns required for buses along their route, to make it easier for non-familiar riders to locate bus stops, or a combination of these; and
- Part-time or reversible lanes that take advantage of spare capacity in the opposite direction of travel when traffic flows on a street are highly directional (e.g., heavy toward downtown in the morning and heavy away from downtown in the afternoon) (AASHTO 2014).

Companion Strategies

Depending on the way the contraflow bus lane is developed, turning movement restrictions (Section 6.2) may be required to prevent potential conflicts between buses and other motor vehicles. Red pavement coloring (Section 7.4) may be desirable to improve the conspicuity of lanes at intersections (to deter motorists from turning into the bus lane by mistake) and between intersections (so that if pedestrians jaywalk, they are at least more aware of the possible presence of buses). Bus signal faces (Section 6.8) may be required to control contraflow buses at signalized intersections. See also the generally applicable companion strategies described in Section 8.1.

Constraints

Developing a contraflow bus lane requires converting a general traffic lane to bus-only use. If a street only has two travel lanes in the direction of travel prior to conversion, there may be insufficient capacity to accommodate traffic in the remaining lane without removing on-street parking and adjusting lane widths to preserve two travel lanes in the normal direction of flow. Streets with three or more lanes are more promising candidates, particularly when good signal progression is provided in the direction of normal flow.

Contraflow bus lanes on one-way streets normally require prohibiting parking and deliveries on the side of the street used by buses and thus have similar potential issues as curbside bus lanes (Section 8.2). Contraflow bus lanes on one-way streets that operate on the left side of the street from a bus's perspective (i.e., on the opposite side of the street from where they would be if the street was two-way) are in an unexpected location from the point of view of motorists and pedestrians and require particular attention to drawing roadway users' attention to approaching buses (AASHTO 2014).

Part-time contraflow lanes typically require a strong directional split of traffic (e.g., ⅔ or more of the roadway's traffic in the peak direction) and the ability to prohibit left turns during hours when the contraflow lane is in operation (AASHTO 2014). Part-time contraflow or reversible operation on arterial streets is not common in the United States, and an extensive outreach effort to motorists may be required as part of the implementation.

Benefits

Contraflow bus lanes on one-way streets typically operate free of turning-traffic, parking, and delivery conflicts and tend to be self-enforcing (AASHTO 2014). Part-time contraflow lanes allow buses to avoid traffic congestion in the normal-flow lanes. See also the general bus lane discussion in Section 8.1.

Cost Considerations

Contraflow bus lanes to the right of opposing traffic would have costs similar to curbside bus lanes. Contraflow lanes where buses operate on the left side of the street may require greater separation from traffic (e.g., pylons, curbing) to keep traffic from inadvertently entering the lane and will require extra measures to draw pedestrians' attention to buses approaching from an unexpected direction. Part-time contraflow lanes may require overhead lane control signals (an additional capital and maintenance cost relative to other bus lane types) or daily installation and removal of pylons (an additional operating cost relative to other bus lane types). See also the general bus lane discussion in Section 8.1.

Contraflow lanes developed on streets as part of a conversion from two-way to one-way operation have experienced a drop in crashes, while contraflow lanes developed on existing one-way streets have sometimes experienced an increase in crashes (AASHTO 2014).

Implementation Examples

Examples of cities with contraflow bus lanes on one-way streets include Chicago, Illinois; Los Angeles, California; Minneapolis, Minnesota; Montreal, Quebec; New York, New York; and Orlando, Florida (AASHTO 2014, Corby et al. 2013).

Some express bus routes in Honolulu, Hawaii, use part-time contraflow lanes on arterial streets; however, these lanes are also open to general traffic. Part-time contraflow lanes were also used on Boulevard Pie-IX in Montreal, Quebec, until the early 2000s; at the time of writing, the street was being reconstructed to implement median bus lanes.

Implementation Guidance

AASHTO (2014) provides design guidance on contraflow bus lanes. A key design consideration, particularly for contraflow lanes that operate on the left side of the street or lanes developed on streets that were previously one-way, is addressing motorist and pedestrian expectancy issues. The main concerns with motorists are turning into the contraflow lane by mistake or making a turn without looking for an oncoming bus. Special lane-use signs and red pavement coloring (Section 7.4) can help with the former; prohibiting conflicting turns or allowing them only on a protected signal phase can help with the latter. For pedestrians, a key concern is that pedestrians crossing at unsignalized or midblock locations (legally or illegally) may spot a gap in the general traffic flow and step off the curb without looking for a bus coming from the opposite direction. Again, red pavement coloring can improve the visibility of the bus lane. Signs and pavement markings can also be applied at legal crossing points; barrier treatments that discourage illegal crossings or strict enforcement of jaywalking laws may be required in locations where jaywalking is prevalent (AASHTO 2014). Outreach and education efforts directed to seniors and persons with disabilities may also be required.

Contraflow bus lanes may require more width than other types of bus lanes in the following situations:

- Lanes that will be used by many buses during peak hours (to provide room for buses to pass a disabled bus in the contraflow lane);
- Lanes where curbs or other barriers exist on both sides of the lane (to give buses more maneuvering room); and
- Lanes in environments where pedestrian jaywalking is common (to give buses more maneuvering room) (AASHTO 2014).

The Implementation Guidance section for reversible bus lanes (Section 8.9) discusses strategies for notifying road users of approaching buses; these strategies may also be applicable to contraflow bus lanes.

Additional Resources

Section 5.5.4 of the *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014) provides design guidance for contraflow bus lanes. Chapter 4M of the MUTCD (FHWA 2009) addresses lane-use control signals. See also the resources generally applicable to bus lanes in Section 8.1.

8.9 Reversible Bus Lane

Description

A single bus lane that serves buses operating in both directions.

Purpose

To provide a bus lane on a roadway where right-of-way constraints prevent providing bus lanes in both directions.

Applications

There are two primary ways that a reversible bus lane can be implemented:

1. Using time-of-day controls so that the bus lane operates (for example) inbound in the morning and outbound in the afternoon. Buses traveling in the off-peak direction use the general traffic lane.
2. Using bus signals to control access to the bus lane in one direction of travel at a time, with the direction alternating back and forth as needed to serve buses. Buses always use the bus lane.

Reversible bus lanes have been implemented in street medians, with curbs or landscaped islands separating the lanes from other traffic; in the center of a street, separated only by lane markings (e.g., in place of a center two-way left-turn lane); and on one side of a one-way street, separated only by lane markings.

Companion Strategies

Reversible bus lanes separated from general traffic only by striping are preferably highlighted in some way, such as with red pavement coloring (Section 7.4) or using Portland cement concrete for the bus lane to create a contrast with darker asphalt concrete in the general traffic lanes. When signals are used to control bus access to the reversible bus lane, transit signal faces (Section 6.8) are typically used to indicate to buses when they may proceed. Transit signal faces and bus-only signal phases (Section 6.9) are frequently used at signalized intersections along the bus lane. Turn restrictions (Section 6.2) that prevent general traffic from crossing the bus lane may also need to be considered. ADA-compliant boarding islands (Section 7.6) will be required to serve stops along bus lanes in the center of the street. See also the generally applicable companion strategies described in Section 8.1.

Constraints

Turning movements across the reversible bus lane may need to be restricted to eliminate or reduce the potential for crashes between buses and turning motorists that did not expect a bus to come from either direction in the lane. Two-directional, single-lane operation that alternates back and forth can greatly reduce the bus frequency that can operate in the bus lane, with the impact increasing as the distance between passing opportunities increases. Converting a curb lane to a reversible bus lane may have impacts on adjacent land uses similar to those of a curbside bus lane (Section 8.2).

Benefits

Reversible bus lanes typically prohibit turns from the bus lane and thereby provide benefits similar to those of median bus lanes (Section 8.7), interior bus lanes (Section 8.4), or curbside bus lanes with right turns prohibited (Section 8.2), depending on the design of the reversible lane. When protected turn phases are required to serve general traffic turns across the reversible lane, the amount of green time available for buses may be less than that available for general through traffic, resulting in longer bus signal delays. When the lane alternates direction through the use of signals, buses may experience delay waiting for a bus from the opposite direction to clear the reversible lane segment. Consequently, ensuring that buses arrive on schedule at the start of a reversible lane segment to use their designated time slot, and designing passing opportunities in appropriate locations for the planned headway to minimize potential waits, are critical factors to address for buses to gain a travel time benefit (and avoid a travel time disbenefit) from the use of a reversible lane. See also the general bus lane discussion in Section 8.1.

Cost Considerations

Reversible bus lanes are typically more expensive to construct than similar types of non-reversible bus lanes (i.e., median, interior, or curbside lanes), particularly when a signal system to control bus access to the lane is required. More signs are needed relative to other types of bus lanes to warn other road users of the unusual operation, and the use of red-colored pavement (Section 7.4) or contrasting pavement colors is suggested to improve the bus lane's conspicuity. Time-controlled reversible bus lanes may require two sets of bus stop infrastructure at each stop—one for when buses are using the bus lane and one for when buses are using the general traffic lane. See the general bus lane discussion in Section 8.1.

Implementation Examples

- **Eugene, Oregon.** Eugene uses reversible bus lanes in sections of the street median on Franklin Boulevard used by its first BRT route, although, to improve bus operations, the length of one of the single-lane segments has been reduced since the line opened. Eugene uses a curbside reversible lane on a one-way portion of East 11th Avenue, with a passing opportunity provided at a station. Eugene uses a center bus lane on a two-way portion of East 11th Avenue, with a passing opportunity provided at a station. Turns across the bus lane are allowed, with special signs used to warn roadway users to look for buses coming from both sides or from behind (see the Implementation Guidance section). When the line first opened, reversible operation was also used in the center of the street on portions of East 10th Avenue and Mill Street, but the route was later split, with one direction on East 11th Avenue and the other direction on East 10th Avenue, in part due to a lack of passing opportunities in this section that affected bus operations.
- **West Valley City, Utah.** UTA operates the 35M MAX bus rapid transit route in the Salt Lake City region. A 1-mile portion of the route operates in bus lanes in the street median of 3500 S. At signalized intersections, the bus lane narrows to a one-lane reversible alignment because right-of-way was required to provide dual left-turn lanes or right- and left-turn lanes for general traffic. Bus access to the reversible sections is controlled by a bus signaling system.
- **Lund, Sweden.** A time-controlled reversible bus lane operates in the center of three-lane Tornavägen northeast of the city center. Buses traveling toward the city center use the lane between 5:00 a.m. and 12:30 p.m., while buses traveling away from the city center use it between 12:45 and 11:00 p.m. Buses travel in the general traffic lanes during times when they are not permitted in the reversible lane (City of Lund 2011). The street has relatively few access points, and most unsignalized intersections and all driveways that do exist are controlled for right-in,

right-out turns only. The one traffic signal in this stretch serves buses on a special bus phase; general traffic is allowed to make left turns from both streets at this location. Reversible operation ends at the south end at a three-leg unsignalized intersection where left turns from and across the bus lane are permitted; the bus lane continues in the inbound direction only past this point, ending just before a traffic signal. Buses merge into the general traffic lane at this point in preparation for making a left turn. At the north end of the bus lane, the general traffic lane merges with the bus lane; general traffic is required to yield to buses.

Implementation Guidance

Reversible bus lanes may be an option where right-of-way constraints prevent the implementation of bus lanes for both directions of travel, but they require attention to certain issues not found with other bus lane types.

Lane Control

Controlling a reversible bus lane by time of day may be an option when traffic on the street is highly directional (e.g., 70/30 in the peak direction) so that buses experience minimal traffic delays when using the general traffic lane(s) in the off-peak direction. As this option requires two sets of bus stop infrastructure at each bus stop—one for when buses are using the bus lane and one for when buses are using a general traffic lane—it is important that passengers be able to easily figure out where and when to wait for a bus. It may also be necessary to consider the possibility that passengers may try to dash across the street if they see the bus approaching the other stop and to develop appropriate countermeasures.

Signal control will be required when bidirectional operation is desired throughout the day. This type of operation requires special attention to coordinating the planned bus headway, the locations where passing opportunities are provided, and the bus schedule, as well as implementing upstream transit-supportive roadway strategies that help buses arrive at a single-lane section on schedule. The goal is to have buses that are traveling in opposite directions meet in sections where passing is possible and not at the single-lane section to avoid one bus being delayed while the other bus uses the single-lane section.

The rail transit single-track capacity method given in the TCQSM (Kittelson & Associates et al. 2013) can be applied to evaluating single-lane bidirectional bus lane capacity by eliminating the rail-specific elements of the method, such as the time to move switches. In general, the longer the single-lane section, the greater the number of single-lane sections along a route, the greater the traffic signal delay within a single-lane section, the lower the speed limit, and the less-reliable the bus arrivals at the start of a single-lane section, the fewer buses on a route that can be served in an hour without creating bus bunching. For a case where the speed limit is 30 mph, buses arrive within 2 min of schedule, and no stops are made within the single-lane section to serve passengers or for traffic signals, a 0.5-mile-long bidirectional single bus lane could support up to 10 buses per direction per hour on a route (i.e., 6-min headways) if the buses are scheduled to avoid arriving at the single-lane section at the same time. As conditions worsen from this case (e.g., traffic signal delays, less-reliable service, a longer single-lane section, a lower speed limit), the minimum bus headway on a route would increase.

Note that it is possible to send more than one bus at a time in the same direction through a single-lane section. For example, for the condition given in the previous paragraph, two routes could operate in the section, each with 6-min headways, and not have bus bunching occur on the individual routes. Because this type of operation will form platoons of buses operating on different routes, bus stops will need be designed to accommodate multiple buses at the same time (Section 7.2).

Turn Restrictions

General traffic turning movements are not suggested to be allowed from reversible bus lanes due to the potential for head-on or sideswipe collisions with buses. Ideally, turns would also be prohibited across reversible bus lanes since this would eliminate potential bus–automobile conflicts. However, when prohibiting turns is not feasible, the following are other options:

- **Protected turn phases at signalized intersections.** Left and right turns from the bus lane's street are preferably made using protected (i.e., arrow) phases to reduce the possibility of conflicts. This option reduces the amount of green time available for bus movements, which will increase bus signal delay.
- **Prohibiting right turns on red at signalized intersections.** Right turns on red that cross a reversible bus lane can be prohibited, either full-time or through the use of blank-out displays that activate when a bus is approaching.
- **Part-time turn prohibitions.** Blank-out turn-prohibition signs can be used at times when a bus is approaching to prohibit turns that cross the bus lane at any intersection.
- **Adding signs to warn side-street road users of potentially conflicting buses.** A proposed new MUTCD chapter on busway grade crossings includes a requirement for a busway crossing warning consisting of a yellow diamond-shaped sign with the picture of a bus, with the option for a yellow rectangular sign underneath with a double-headed arrow indicating two-way operation (NCUTCD 2014a). Until included in the MUTCD, agencies would need to apply to FHWA to experiment with the signs (see Appendix D).
- **Adding blank-out signs to warn road users of potentially conflicting buses.** A proposed new MUTCD chapter on busway grade crossings includes the option for a blank-out sign that displays a flashing picture of a bus, the text "Bus Coming," or both when a bus approaches (NCUTCD 2014a). This sign would be used similarly to existing blank-out signs warning of approaching light rail trains (MUTCD, Section 8B.19) and could be used in conjunction with main- and side-street turning movements and pedestrian crossings. Until included in the MUTCD, agencies would need to apply to FHWA to experiment with the sign. Audible warnings for the benefit of visually impaired pedestrians could also be considered in conjunction with the blank-out signs.

Pedestrians

Consideration should be given to drawing pedestrians' attention to the potential for buses approaching from either direction, particularly when reversible curbside bus lanes are used. The static and active warning signs described previously are potentially applicable, as are pedestrian-focused word messages on the sidewalk (e.g., "Look Both Ways"), accessible pedestrian signals, and outreach and education efforts directed to seniors and persons with disabilities.

When bus stops are located on boarding islands in the center of the street at unsignalized intersections, marked pedestrian crosswalks may be desirable. As discussed earlier in the Lane Control subsection, when two sets of bus stops are provided in conjunction with time-controlled reversible bus lanes, it may be necessary to consider the possibility that passengers may try to dash across the street if they see the bus approaching the other stop and to develop appropriate countermeasures.

Additional Resources

Chapter 8 of the TCQSM (Kittelson & Associates et al. 2013) provides a method for determining single-track rail transit capacity that is adaptable to determining the minimum headway feasible for reversible bus lane operations. See also the resources generally applicable to bus lanes in Section 8.1.

APPENDIX A

Understanding Traffic Engineering Practice (for Transit Professionals)

This appendix is intended to provide transit professionals a description of the traffic engineering profession as it relates to implementing transit-supportive roadway strategies. It uses the somewhat narrow terminology of *traffic engineering* even though most professionals use the broader terminology of *transportation engineering*, which conveys a more multimodal perspective. However, because transportation engineering also applies to transit, the narrower term of traffic engineering is used to denote the operation of the surface transportation system for pedestrians, bicycles, all street-operating types of transit, trucks, and automobiles.

The first section covers why traffic engineering standards exist, how they are applied, and available opportunities to vary from the standards to achieve better project outcomes. The second section covers reference documents that provide both standards and guidance on traffic engineering practice. The third section describes common types of analysis tools used in planning, operations, and design. The final section provides a primer on how traffic signals operate and how transit operations can be integrated into traffic signal operation.

A.1 Traffic Engineering Practice

Traffic engineers have a long history of operating the surface transportation system for all modes of transportation. This practice has resulted in standards, guidance, state practice, and local practice. Traffic engineering practice has evolved over the years and continues to evolve to this day. This section is intended to help transit professionals understand the traffic engineering point of view in order to better communicate and, ultimately, to provide a better transportation system for all users.

Agency Stakeholders

It is important to understand that the transportation system can be viewed from many perspectives other than that of the agency (e.g., transit agency, city public works department, state DOT). These perspectives can be seen as competing unless one steps back and realizes that the broader view of transportation is that of the user. Users are less interested in agency and jurisdictional boundaries and more focused on completing a trip that often crosses agency and jurisdictional boundaries and may shift modes one or more times over its course. It is therefore desirable to establish multi-agency operations working groups to exchange information and work together on common problems in order to achieve mutually beneficial operational strategies.

User Perspective

Transportation users consist of many types, including some who change transportation modes (e.g., motor vehicle, bicycle, pedestrian, transit) two or more times in making a trip (e.g., drive to a park-and-ride lot, take transit to a stop near their destination, and walk to their destination). Public-sector traffic engineers typically work within their agency jurisdiction and may focus on a specific modal perspective such as bicycles. Transit is clearly one of several system users. Ultimately, the user is best served by a collaborative approach between all agencies responsible for the operation of the transportation system.

Standards, Guidance, and State or Local Practices

Traffic engineering practitioners works with three basic types of documents: standards, guidance, and (depending on the agency or jurisdiction) state or local practices. These documents are discussed in more detail in Section A.2. However, it is important to understand from the start the differences in weight and interpretation of these types of documents. The MUTCD (FHWA 2009), for example, is a set of standards that also provide guidance and options. Standards generally have no room for variation or interpretation by the engineer, other than possibly through a formal design exception process. Guidance is essentially recommendations for best practice, with room for interpretation on their applicability to specific locations. State standards typically exist for use on state facilities but may also apply to other facilities when funds originate with the state or are passed through the state. Local standards are typically how local agencies interpret guidance for their jurisdictions.

Multimodal Perspectives

As vehicular traffic has become more congested and options for improving capacity limited, practitioners have become more focused on multimodal uses of the system, especially in areas where non-automobile modes are encouraged. This evolving area of practice is changing agency standards to provide designs that are more accommodating of non-automobile modes and working toward developing complete networks for all modes.

While land use goals may favor increased density and a multimodal system, transportation goals continue to be dominated by automobile mobility measures. In some cases, the need to maintain set levels of automobile mobility is at odds with creating an environment friendly to other models of travel. For instance, to meet auto-based operations standards at an intersection, a roadway agency may need to add turn lanes or widen the roadway approaches, introducing longer crossing distances and potential conflict points for pedestrians. As another example, some roadway agencies may find it challenging to implement transit signal priority if it results in some delay increases for automobiles. Increasingly, however, projects needed to meet automobile mobility standards may not be supported by the community or may be counterproductive to creating a multimodal environment.

To respond, many agencies are starting to look at multimodal performance measures and alternative methods of measuring performance. Considering multimodal performance allows practitioners to promote improvements that will enhance the transportation system for all modes and have more flexibility to pursue projects that provide the most benefits to users throughout the day rather than just focusing on vehicle performance during peak conditions.

In addition, a focus on Complete Streets is emerging in the traffic engineering world. Complete Street policies intend to "develop integrated, connected networks of streets that are safe and accessible for all people, regardless of age, ability, income, ethnicity, or chosen mode of travel" (Seskin and McCann 2013). As the practice evolves, more jurisdictions are recognizing that beyond Complete Streets it is important to develop complete networks. While it may not be feasible or cost-effective to design every street to accommodate all modes, a "network context considers all users' expectations of the entire network" (Active Transportation Alliance 2012). A network approach to Complete Streets recognizes that instead of trying to make each street perfect for every traveler, communities can "create an interwoven array of streets that emphasize different modes and provide quality accessibility for everyone" (Seskin and McCann 2013).

More transportation agencies are adopting policies aimed at considering all users in transportation projects, encouraging street connectivity for all modes, and establishing operations performance standards with measurable outcomes. Complete Street/network policies provide an opportunity for traffic engineers to work with other transportation professionals to pursue multimodal projects such as transit-supportive roadway strategies. This heightens the importance of creating and maintaining connections between traffic engineers and transit agency staff, which is one of the objectives of this guidebook.

A.2 Reference Documents

The following are standard reference documents that guide traffic engineering practice.

Manual on Uniform Traffic Control Devices

The MUTCD is the most authoritative U.S. reference for traffic engineering practice regarding traffic signals, traffic signs, and traffic markings. The MUTCD is published by the FHWA under 23 Code of Federal Regulations (CFR), Part 655, Subpart F. The purpose of this CFR is to prescribe "policies and procedures of the FHWA to obtain basic uniformity of traffic control devices on all streets and highways" (23 CFR 655.601, Purpose). State transportation agencies are required to either:

- Adopt the national MUTCD as their standard;
- Adopt the national MUTCD, along with a state supplement that may specify which of several allowable options are to be used; or
- Adopt a state traffic control device manual that is based on the national MUTCD and is in substantial conformance with the national MUTCD.

The MUTCD is updated periodically to reflect new technologies, traffic control tools, and traffic management practices. When a new national MUTCD is published, states have 2 years to adopt the updated document.

The MUTCD provides four types of information:

- **Standards.** Provided in bold text in the MUTCD, these are hard requirements with no room for interpretation. For example, Section 4D.27, Preemption and Priority Control of Traffic Control Signals, states that "During the transition into preemption control . . . the yellow change interval, and any red clearance interval that follows, shall not be shortened or omitted" (FHWA 2009). Standards may use the word *shall* to denote a "required, mandatory, or specifically prohibitive practice" (Section 1A.13). The MUTCD's traffic signal warrants are standards that state that the need for a traffic signal "shall be considered" if the warrant criteria are met.
- **Guidance.** Provided in italic text in the MUTCD, guidance describes recommended best practices that provide some room for interpretation. Some guidance is less specific and requires local interpretation and engineering judgment, such as "Traffic control signals operating under preemption control or under priority control should be operated in a manner designed to keep traffic moving" (Section 4D.27). Guidance may use the world *should* to denote a "recommended, but not mandatory, practice in typical situations, with deviations allowed if engineering judgment or engineering study indicates the deviation to be appropriate" (Section 1A.13).
- **Options.** Provided in standard text in the MUTCD, options are "permissive condition[s] and carr[y] no requirement or recommendation" (Section 1A.13). Option statements sometimes

provide modifications to standard or guidance statements to provide flexibility for jurisdictions to fit specific, local needs. For example, Section 4D.26, Yellow Change and Red Clearance Intervals, provides a standard practice for developing all-red intervals at traffic signals. An option is provided that states "The duration of a red clearance interval may be extended from its predetermined value for a given cycle based upon the detection of a vehicle that is predicted to violate the red signal indication" (FHWA 2009). The words *shall* and *should* are not used in option statements.
- **Support.** Provided in standard text in the MUTCD, support statements provide information and do not "convey any degree of mandate, recommendation, authorization, prohibition, or enforceable condition" (Section 1A.13).

The MUTCD is divided into nine parts that cover signs, markings, traffic signals, and traffic control devices. Sections of particular relevance to bus operations are:

- Chapter 4C, Traffic Control Signal Needs Studies;
- Section 4D.27, Preemption and Priority Control of Traffic Control Signals; and
- Chapter 8, Traffic Control for Railroad and Light Rail Transit Grade Crossings, which includes details on light rail signal displays that are also an option for certain types of bus operations.

The full version of the MUTCD is available online at mutcd.fhwa.dot.gov.

It is possible to experiment with new concepts that are not currently provided in the MUTCD. This process for experimentation is defined in Section 1A.10, Interpretations, Experimentations, Changes, and Interim Approvals. In summary, jurisdictions requesting approval for experimentation of a new traffic control device are required to submit their request to the FHWA. If approved, the requesting jurisdiction may install the experimental traffic control device, evaluate its performance, and provide regular reports to the FHWA. If granted, interim approval allows for interim use of the device pending official rulemaking. Requests are considered based on "the results of successful experimentation, results of analytical or laboratory studies, and/or review of non-U.S. experience with a traffic control device or application" (Section 1A.10). For example, bicycle signals are an area of currently evolving practice that has been partially accepted for limited use by FHWA. Jurisdictions seeking permission to use bicycle signals must comply with the conditions set forth by the FHWA for their interim use and maintain an inventory list of where bicycle signals are installed.

AASHTO Publications

The American Association of State Highway and Transportation Officials publishes *A Policy on Geometric Design of Highways and Streets* (AASHTO 2011), which is commonly known as the Green Book because of the document's color. This is the definitive guidance for state departments of transportation. It is also used by many local agencies by reference or by using or adapting its guidance. The Green Book has evolved over the years from a largely auto- and truck-oriented document to a more multimodal document. Much of its guidance was developed to ensure adequate geometric standards for higher speeds and vehicles, including multi-unit trucks. Its influence on urban practice has been significant, especially on roadways operated by state departments of transportation. However, many local agencies have modified this guidance to reflect the more confined space available in urban environments. The Context Sensitive Solutions approach is the application of appropriate designs in urban or otherwise constrained environments.

AASHTO also publishes design guidelines for pedestrian facilities (AASHTO 2004), bicycle facilities (AASHTO 2012), and transit facilities (AASHTO 2014). Chapter 4 of *TCRP Web-Only Document 66* provides possible changes to the AASHTO Transit Guide resulting from the research conducted by TCRP Project A-39.

Another AASHTO publication is the *Highway Safety Manual* (HSM, AASHTO 2010), which can be used to quantitatively assess and predict crash frequency and severity based on traffic volumes and roadway characteristics. This manual also provides crash modification factors (CMFs), which quantify the change in average crash frequency expected with a geometric or operational modification to a roadway. CMFs are provided in the HSM for a variety of roadway strategies, and additional CMFs are available online at the FHWA's CMF Clearinghouse (www.cmfclearinghouse.org). The current state of research is limited with regard to the safety implications of transit-supportive roadway strategies; however, the HSM can be used to evaluate changes in roadway or intersection characteristics introduced in conjunction with these strategies, and the CMF Clearinghouse includes some transit-related CMFs, such as for implementing transit signal priority and restricting turning movements at transit-serviced locations.

Highway Capacity Manual

The *Highway Capacity Manual 2010* (Transportation Research Board 2010) is frequently used by traffic engineers to evaluate roadway operations and is also often referenced by roadway agencies when setting their operational standards for roadways. As with other traffic engineering references, the HCM has evolved over time to provide more analysis methods and performance measures for non-automobile modes. Typical performance measures defined by the HCM for urban streets and roadways are:

- **Delay.** Delay is defined generally as "additional travel time experienced by a driver, passenger, bicyclist, or pedestrian beyond that required to travel at the desired speed" and more specifically as *control delay*, which is "delay associated with vehicles slowing in advance of an intersection, the time spent stopped on an intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate to their desired speed."
- **Speed.**
- **Volume-to-capacity ratio.** Volume-to-capacity ratio can be thought of as the percentage of an intersection's or intersection approach's capacity that is in use or in demand.
- **Level of service (LOS).** LOS assigns values of a specified performance measure one of six ranges, represented by the letters A through F, "with LOS A representing the best operating conditions from the traveler's perspective and LOS F the worst." For intersections, automobile LOS is based on control delay; for roadways, automobile LOS is based on average speed; and for non-automobile modes, LOS is based on the mode's LOS score.
- **Modal level-of-service scores.** These scores blend multiple factors into a measure reflecting average modal user satisfaction with a defined set of conditions; for example, the transit level-of-service score incorporates pedestrian access, bus stop amenities, bus frequency, bus reliability, bus speed, and onboard crowding as factors (Transportation Research Board 2010).

State and Local Design and Operations Standards

State departments of transportation and local roadway agencies typically develop their own design manuals that reflect their agency's perspective of the traffic engineering guidance provided in the Green Book and other sources. For example, these manuals may specify that certain options provided in the national guidance should not be used by the agency, or they may specify design standards that are higher than the minimums provided in the national guidance.

These roadway agencies also specify operations standards for their roadways, which specify the minimum operation considered by the agency to be acceptable for a particular type of roadway. Most roadway agencies have traditionally used either automobile LOS or volume-to-capacity ratio for their standards. However, as roadway widening becomes more challenging and expensive to implement and, in some cases, conflicts with state and local goals regarding livability and sustainability, some jurisdictions have begun to adopt alternative measures (e.g., measures of travel time reliability or vehicle miles traveled) or to consider a broader range of measures (e.g., person delay, multimodal LOS) as part of their decision making.

A.3 Analysis Tools

A common theme expressed in the transit agency surveys conducted for this project was that transportation engineers are typically easy to work with when one comes prepared with a traffic analysis that demonstrates how a proposed transit-supportive roadway strategy will likely affect roadway operations. A variety of analysis tools exist for evaluating roadway operations, ranging from simple to complex in terms of both information required and computational complexity, and roadway agencies will often specify what tool to use in what situation. Typical tools are:

- **Regional transportation planning models.** These models are often used to identify long-range transportation needs by mode and are based on assumed land use, population, and employment patterns. They can also be used to assess how traffic patterns may shift between facilities and modes when changes are made to the transportation system (e.g., converting a general travel lane on a street to a bus lane).
- **HCM and HCM-like methods.** These tools implement the HCM or other methods for evaluating roadway operations by using computer software to perform the calculations. Users typically have to provide detailed information about traffic demand patterns, roadway characteristics, and traffic signal timing, although default values may be substituted in some cases where these data are unknown. These tools are often used to demonstrate that a proposed project will meet a roadway agency's operational standards.
- **Simplified planning analysis tools.** These tools are typically simplified versions of HCM methods that are implemented in the form of tables, spreadsheets, or computer programs and that require relatively few data inputs but produce correspondingly less-precise results than other methods. They are often used to quickly evaluate a large set of alternatives for sufficiency and to produce loose performance measure estimates when a more precise answer is not needed.
- **Microsimulation.** These tools model the movements of individual roadway users (e.g., autos, buses, pedestrians, bicyclists) and produce the most-precise results of any tool. Their accuracy depends in great part on how well the model is calibrated to existing conditions. They require significant amounts of time and data to implement and so are usually not used for evaluating large numbers of alternatives. Instead, they are often used to confirm the results of a less-precise tool, to address situations not directly addressed by HCM methods (e.g., traffic signal operations with transit signal priority), and to generate visualizations of roadway operations.

To assess the complexities of multimodal operations, microsimulation is often needed in conjunction with traffic signal optimization tools. Traditional optimization tools can often be used as a starting point for traffic signal operation. However, these tools cannot optimize for multimodal operations since the competing operational objectives for each user type must be prioritized based on local needs. Microsimulation can be used to evaluate alternative operational strategies (e.g., transit signal priority, curb extensions) in terms of a broader range of outcomes (e.g., reduced person-delay, improved transit reliability) than is possible with optimization tools that solely optimize vehicle delay.

A.4 Traffic Signal Timing Concepts

The following is a summary of signal timing concepts from *NCHRP Report 812: Signal Timing Manual* (Urbanik et al. 2015). Signal timing is the process of selecting appropriate values of timing parameters to implement in traffic signal controllers and associated traffic signal system software. Appropriate signal timing programs ensure that signal timing parameters are appropriate over the life of the traffic signal system. While effective signal timing is necessary, it will not automatically sustain a successful signal timing program. A signal timing program includes all aspects of traffic signal implementation, operations, and maintenance consistent with community needs. A successful program requires agency staffing and maintenance funding that is consistent with the level of service planned. Signal timing typically needs to be reviewed and be updated when traffic volumes and patterns change or when community priorities change.

The signal timing produced by software largely reflects the system user priorities (generally some version of vehicle delay) built into the software's signal timing optimization model. These priorities may or may not fit the needs of the actual operating environment or users (including pedestrians, bicycles, and transit).

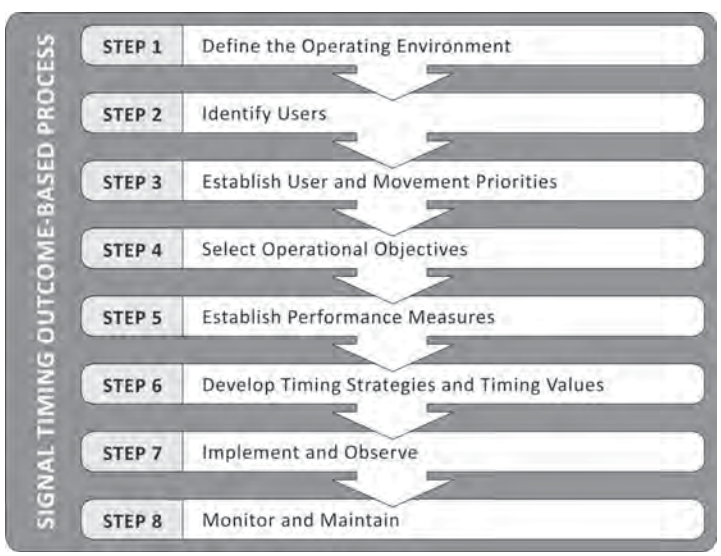
Signal Timing Approach

An outcome-based approach to signal timing (summarized in Figure A-1) allows the practitioner to develop signal timing based on the operating environment, users, user priorities by movement, and local operational objectives. Performance measures are then used to assess how well the objectives are being met. Once the objectives and performance measures are established, timing strategies and timing values can be developed. The final steps of the process involve implementation and observation (i.e., determining if the timing strategies and values are working) as well as monitoring and maintenance in order to sustain operations that meet the operational objectives.

This process was developed with an understanding that there is not a one-size-fits-all method for signal timing. The approach is described in more detail in *NCHRP Report 812: Signal Timing Manual*, but brief descriptions of the eight steps in the outcome-based process and associated considerations are provided here.

Step 1: Define the Operating Environment

Signal timing should reflect the character of the timing location, so the outcome-based approach begins with an assessment of the operating environment. The operating environment



Source: *NCHRP Report 812: Signal Timing Manual*, 2nd Edition (Urbanik et al. 2015).

Figure A-1. Signal timing outcome-based process.

goes beyond physical location characteristics and includes goals of the local operating agency and its regional stakeholders.

Step 2: Identify Users

The process continues with the identification of primary users at the focus intersections. This approach allows all users (people on foot, including seniors and persons with disabilities, bicyclists, transit vehicles and passengers, truck drivers, and motorists) to be considered in the signal timing process. This is consistent with the multimodal perspective discussed earlier in this appendix.

Step 3: Establish User and Movement Priorities

Priorities should reflect the local operating agency and regional stakeholder goals for mobility. Priorities should be established by movement for the primary users by location and time of day. For example, in a central business district, pedestrians might have the highest priority, while in a suburban environment, through-vehicle movements on an arterial might have the highest priority during peak hours and a lower priority off-peak.

Step 4: Select Operational Objectives

Once priorities are established, the process requires the establishment of operational objectives (e.g., pedestrian safety, vehicle mobility) by location and time of day. Non-vehicle–oriented operational objectives are often more difficult to assess because of their qualitative nature; however, performance measures can be selected for qualitative as well as quantitative assessment.

Step 5: Establish Performance Measures

Traditional optimization tools generally focus only on simple vehicle-oriented performance measures because they are easy to quantify and, therefore, easy to optimize. However, vehicle stops and delays may be less important than transit and pedestrian performance in a central business district or other existing or developing areas with significant pedestrian, bicycle, and transit activity. The practitioner needs to make appropriate adjustments to the traffic signal timing process to account for the operating environment and user priorities.

Step 6: Develop Timing Strategies and Timing Values

Once operational objectives and their associated performance measures have been determined, the process continues with the development of signal timing strategies (such as minimizing cycle length or favoring arterial through traffic) and with the selection of appropriate timing values. The options for signal timing may be restricted by standards or guidance. For example, the MUTCD provides guidance on the pedestrian clearance interval and provides standards for determining the duration of the yellow change interval and red clearance interval (FHWA 2009).

Step 7: Implement and Observe

The next step is implementing the signal timing values and making final adjustments to the timing parameters based on field observation (since it is important to understand that analytical tools do not capture all the subtleties of actual field conditions). However, it is equally important not to make changes based on a single field observation since traffic characteristics can vary from hour to hour and day to day.

Step 8: Monitor and Maintain

After implementation, a successful program requires ongoing monitoring and maintenance. Collecting periodic (at least annual) volume data at a midblock location on each arterial or subsystem is suggested to determine if shifts in traffic characteristics may have occurred and further investigation is necessary. A good maintenance management system can identify communication and detection issues, which are often a significant contributor to poor signal operation.

Signal Timing and Transit-Supportive Roadway Strategies

Signal timing is a complex process that allocates time and space to various roadway users based on the operating environment and movement priorities. When choosing to implement a signal-related transit-supportive strategy, collaboration is required between traffic and transit engineers. The technical requirements include understanding and providing the necessary capabilities to implement preferential treatment. This is typically done by first developing a concept of operations. The concept of operations is a nontechnical document that essentially describes what the needs of the system are and how they will be met. Once a concept of operations is agreed to by all stakeholders, the technical requirements to implement the concept of operations can be developed.

It should be understood that there are many practical realities to be addressed in the process of developing preferential treatment of transit. Compromises may need to be made based on all users of the system, including pedestrians. Pedestrians are present in many operating environments where transit priority is warranted and present certain constraints based on mobility requirements that must be met (e.g., MUTCD-specified pedestrian clearance times). In addition, motorized vehicle operations may be affected by transit-supportive strategies. These and other considerations are discussed in Chapter 4.

In order for transit priority to be successful, important capabilities generally need to be provided by the transit system. These include:

- Integration of a transit automatic vehicle location system to determine if the transit vehicle is running late. This is important because priority for on-time vehicles is unnecessary and limits the signal's ability to provide priority to late transit vehicles arriving in the same time period.
- Ability to communicate a vehicle's estimated time of arrival to the traffic signal system. This ensures that the traffic signal is able to process the request in a timely manner.

The potential transit detection technology may be constrained by existing technology used for emergency vehicles. That is but one example of the need for a concept of operations and ultimately the development of specific technical requirements. The capabilities of the traffic signal system may also be an important consideration in how transit-supportive strategies may be implemented. Each traffic signal system has capabilities that are defined by the vendor of the system. It is generally not possible to significantly change the capabilities of the traffic signal system. Again, the concept of operations process allows stakeholders to come to an understanding of what is possible, either within the current capabilities of the system or by modifying the system. Significant modifications to or replacement of the system may require substantial financial resources from stakeholders.

In summary, preferential treatment of transit at traffic signals is something that requires stakeholders to come to an agreement on what is possible and how it might be implemented. The process can be relatively simple or relatively complex based on the realities of each stakeholder's current capabilities.

APPENDIX B

Understanding Transit Operations (for Transportation Engineers and Planners)

This appendix is intended to provide transportation engineers and planners a better understanding of transit operations, describe how transit-supportive roadway strategies can help provide better transit operations, and explain why improving operations is an important goal of transit agencies.

The first section contrasts the service-oriented nature of transit operations to the facility-oriented nature of roadways and discusses how operating costs have much greater importance for transit service than for roadways. The second section presents a few basic bus route scheduling concepts that illustrate the direct relationship between bus travel speeds on a route and the route's operating costs. The third section discusses transit performance considerations related to transit-supportive roadway strategies. The final section highlights transit-specific references that may be consulted when planning and designing transit-supportive roadway strategies.

B.1 Transit as a Service

A key difference between roadway and transit agencies is that roadway agencies primarily provide *facilities* that roadway users can travel on at their convenience, while transit agencies primarily provide a *service* that is only available at designated times and places. If a roadway agency's maintenance budget is cut by half for a year, existing roadways (the agency's capital investments) may still be as usable as they were the previous year, although they will slowly degrade in quality and be more expensive to repair the following year. If a transit system's operations budget is cut by half for a year, the system's buses (the system's capital investments) will still be around, but funding will only be available to operate half of them, resulting in an immediate need to cut service, with a correspondingly severe decrease in the quality of service experienced by passengers.

Because transit is a service, the cost of providing that service is a key concern of transit agencies. The largest component of a transit agency's operating cost is the labor required to drive the buses, although other costs such as consumable items required by buses (e.g., fuel, oil, tires) and labor costs shared by multiple buses (e.g., bus maintenance staff, schedulers, planners, customer service staff) also contribute. As a result, the hourly cost of keeping a bus in service is an important performance metric for transit agencies; in 2012, the average cost of operating one bus for 14 hours a day, 5 days a week, for an entire year was approximately $450,000, based on National Transit Database data.

Given that the cost required to operate a bus over its useful life (typically around 12 years) is an order of magnitude higher than the capital cost of the bus itself, transit agencies are very interested in using buses as efficiently as possible while they are in service. The faster that a bus can travel, the fewer buses are needed to provide service at a certain headway on a route of a certain length, as is shown in the next section.

B.2 Basic Route Scheduling Concepts

Cycle Time Concepts

Assume for the sake of example that a transit agency operates a route that is 6 miles long and that generates sufficient ridership to require service every 10 min (i.e., a bus headway of 10 min, corresponding to a frequency of 6 buses departing a stop per hour). If the average speed that a bus operates along the route during peak periods is 8 mph, including stops to serve passengers, delays at traffic signals, and other delays due to traffic interference, how many buses are required to operate on this route?

The answer to this question requires determining the cycle time, the time for a bus to make a round trip on the route (running time), the time for an adequate break (layover) for the driver, and any additional time necessary to ensure that the bus can begin its next trip on time (schedule recovery time). These components are determined as follows:

- **Running time.** On a 6-mile route, a bus traveling 8 mph requires 0.75 h (45 min) to travel the route from one end to the other. Therefore, the round-trip running time is twice this amount, or 90 min.
- **Layover time.** The required minimum layover time will be specified in the drivers' contract, but a typical rule of thumb is 10% of the running time (Boyle et al. 2009), which in this case is 9 min. The layover could be scheduled to occur all at once at the end of the round trip or could be scheduled to be split between the ends of the route, which will be assumed for this example.
- **Schedule recovery time.** If travel times on the route are highly variable, the layover time may not be sufficient to ensure that a bus can depart on time for its next trip. In that case, additional schedule recovery time may be required. For the time being, it will be assumed that travel times are regular enough that no schedule recovery time is required.

The sum of these three components, 99 min, cannot be divided evenly by the desired headway, 10 min, and therefore the cycle time is rounded up to the next highest value that can be divided evenly, which in this case is 100 min. The required number of buses to operate the route is the cycle time divided by the headway, or 10 buses. Figure B-1 shows how these buses are distributed along the length of the route. Although the spatial distance between buses may vary between buses along the route (depending on how fast buses can travel in each segment of the route), the time headway stays constant at 10 min if good schedule reliability can be maintained.

Impact of Changes in Bus Speeds on Short-Headway Routes

What would happen if the average bus speed could be increased from 8 mph to 9 mph? In this case, the round-trip running time would drop from 90 min to 80 min, the minimum layover

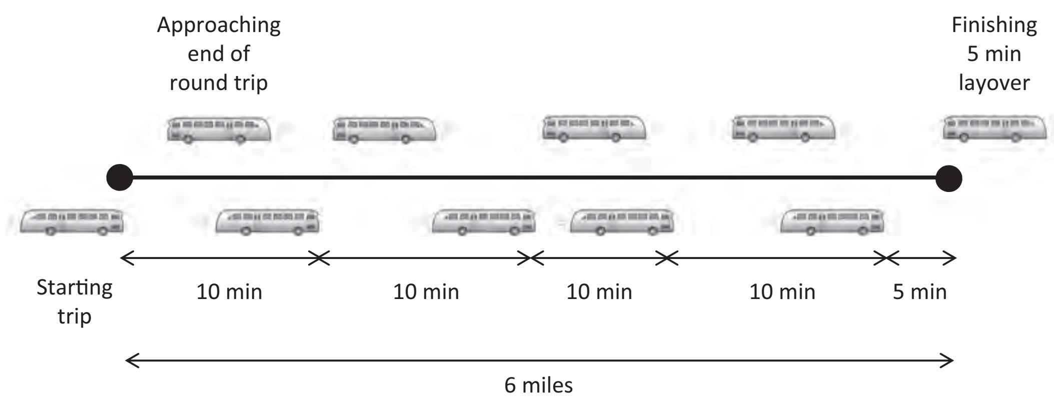


Figure B-1. Example distribution of buses on a route with 10-min headways.

time would become 8 min, and the cycle time would become 90 min. In this case, only nine buses would be needed to operate the route at 10-min headways. The bus that is saved could be used to improve service on another route (attracting more ridership and fare revenue for the same operating cost) or could be taken out of service (reducing overall operating costs by one peak-period bus).

On the other hand, what if traffic congestion caused average bus speeds to drop from 8 mph to 7½ mph? The round-trip running time would increase from 90 min to 96 min, the minimum layover time would be 10 min, and the cycle time would need to be 110 min to accommodate 10-min headways, requiring 11 buses in all. Now, the transit agency would need to add a bus to the route, which (1) might require purchasing an additional bus and (2) would definitely add one bus's worth of operating costs each year.

If the transit agency's budget does not permit adding a bus, service would need to be cut back to 12-min headways. Although this may not seem like much, each bus would need to serve 20% more passengers per trip. This means that if all the seats were taken on average at the busiest point on the route, now the aisle would be filled with passengers on average, and some trips would need to bypass stops with waiting passengers because there would be no room for them (because passengers do not arrive at an even rate over the course of an hour). Service quality would drop and some passengers would be driven away, reducing transit agency revenue.

A similar scenario involving adding buses or cutting service would occur if average bus speeds stayed the same but travel times became more variable, requiring inserting some schedule recovery time into the cycle time in addition to the existing layover time to ensure that buses could depart the ends of the route on time and that schedule reliability did not suffer.

Impact of Changes in Bus Speeds on Longer-Headway Routes

Transit on most routes is not operated as frequently as given in the previous examples. When a route is scheduled efficiently, the required round-trip time savings may need to be close to the value of the route headway to be able to save a bus. For example, if the route operates every 15 min, the required time savings may need to be 15 min or a little less (depending on how much rounding up is needed to produce a workable cycle time) to be able to save a bus.

In many cases, it may not be feasible to save enough time using a package of transit-supportive roadway strategies to remove a bus from a route. However, this does not mean that saving time is useless. Instead, the time savings provide a buffer to counteract the effects of increasing traffic congestion that would otherwise reduce average bus speeds and require the transit agency to add a bus to a route. This, in turn, pushes the need for adding buses into the future, thereby postponing the need to purchase additional buses and postponing the need for increased operating costs. The time savings may also be noticeable to customers, resulting in improved ridership.

An evaluation of TriMet's streamlining program (Koonce et al. 2006), which involved consolidating stops, installing curb extensions, providing transit signal priority, and using the most technologically advanced buses in the fleet on selected routes, found that insufficient time was saved to save a peak-period bus on any of the 12 routes. However, the time that was saved postponed the need to add buses to these routes by approximately 8 years, equivalent to $13.4 million in saved operating costs over that time, plus avoiding the need for capital expenditures for new buses for those routes during that time. In addition, new ridership was generated that resulted in $1.7 million in additional fare revenue, and the streamlined routes' on-time performance declined at half the rate of similar non-streamlined routes. All of these provide meaningful benefits for the transit agency and its passengers.

B.3 Transit Performance

Agency Stakeholders

There are a variety of stakeholders with vested interests in transit operations and performance. The community at large is interested in, among other things, transit's role in providing transportation choices to members of the community, the transit agency's role as a creator and supporter of jobs, transit's role in reducing the environmental impact of the overall transportation network, and how service is distributed throughout the transit service area. Roadway agencies' interests include the impact of transit vehicles on roadway operations and the damage they could cause to pavement, particularly at bus stops. Passengers are interested in having service provided frequently, reliably, comfortably, and conveniently close to their origins and destinations (Kittelson & Associates et al. 2013).

These perspectives can be seen as competing unless one steps back and realizes that the broader view of transportation is that of the user. Users are less interested in agency and jurisdictional boundaries and more focused on completing a trip that often crosses agency and jurisdictional boundaries and may shift modes one or more times over the course of the trip. It is therefore desirable to establish multi-agency operations working groups to exchange information and to work together on common problems in order to achieve mutually beneficial operational strategies.

Customer Service and Ridership

Transit agencies are typically focused on providing the best quality of service feasible to ensure good customer service that maintains and builds ridership. Meeting ridership targets is essential for revenue purposes since transit agencies are typically reliant on passenger fares for a portion of their funding, and some grant funding is also linked to ridership. Key elements of transit service quality include:

- Safe, secure, and convenient access to transit stops (spatial access);
- Service frequency and days and hours of service (temporal access);
- Service reliability (e.g., on-time performance, ability to make transfer connections);
- Travel time and speed;
- Comfort (e.g., ability to get a seat); and
- Cost (e.g., fare) (Kittelson & Associates et al. 2013).

All of these factors influence ridership to some extent, although more research is needed. Related to factors influenced by transit-supportive roadway strategies, ridership tends to improve by 0.3% to 0.5% for every 1% reduction in travel time (Kittelson & Associates et al. 2007), while improvements in travel time variability documented in the literature have had little or no impact on ridership (Kittelson & Associates et al. 2013), although some positive impact might be expected.

Performance Metrics

The following are some key performance metrics used by transit agencies that can be affected by transit-supportive roadway strategies.

Ridership

Ridership is typically measured as the number of transit vehicle boardings; thus, a person using two transit vehicles over the course of a one-way trip is counted as two boardings. Ridership is a key metric for transit agencies since it directly affects agency revenue and is a primary indicator of how well the transit agency is performing one of its core functions: meeting the mobility needs of the residents and employees located within its service area. Ridership is also a key determinant of service levels on a transit route; if ridership drops below a transit agency's standard, service may eventually need to be cut, while if ridership grows sufficiently that quality of service is affected (e.g., crowded vehicles, slower travel times due to serving more passengers), service may need to be added.

Cost-Related Metrics

As a provider of service, transit agencies are interested in the cost of providing that service, and many of the most commonly used transit performance metrics involve operating costs (e.g., operating cost per revenue hour, revenue mile, and boarding). Cost per hour is minimally affected by transit-supportive roadway strategies, cost per mile is affected to the extent that strategies reduce the number of stops made and thus improve fuel economy and reduce vehicle wear and tear, and cost per boarding is affected when improvements to a route's speed attract new ridership.

Reliability

Because most transit service is provided according to a timetable, passengers have an expectation that they will arrive at their destination at a particular time. Passengers perceive unexpected waiting time as being 2 to 5 times more onerous than unexpected in-vehicle travel time (Kittelson & Associates et al. 2013). A common performance metric representing the passenger point of view is on-time performance (e.g., percent of trips arriving within a specified number of minutes of the scheduled time). Some transit agencies use travel time percentiles in determining how much schedule recovery time to include in the schedule (Boyle et al. 2009).

Travel Time

The time required to travel a route is critical in determining the number of buses required to operate the route, as was discussed earlier. In addition, the faster a bus can travel a route, the longer the distance that can be traveled in a given amount of time, which has implications for how much area can be served by a route in a given time.

B.4 Reference Documents and Analysis Tools

The transit industry does not rely on standard national reference documents to the degree that the traffic engineering profession does. When evaluating transit-supportive roadway strategies, practitioners often use the documents and tools discussed in Appendix A. Nevertheless, there are a few additional types of transit-focused documents that are worth highlighting.

Transit Capacity and Quality of Service Manual

The TCQSM (Kittelson & Associates et al. 2013) is the transit counterpart to the *Highway Capacity Manual* (Transportation Research Board 2010). It provides a complete set of methods for evaluating the capacity of transit services and facilities and presents a framework for evaluating transit quality of service from a passenger point of view. The toolbox chapters of this guidebook identify when the TCQSM may be applicable for evaluating the potential benefits of particular strategies; in particular, it can be used to estimate the following:

- Average bus speeds on different types of bus lanes,
- Delays associated with waiting for a gap to re-enter traffic from a bus stop,

- Required bus stop length to serve a given number of buses at a specified level of reliability, and
- Impacts of changes in bus speeds on the quality of service perceived by passengers.

The TCQSM's speed-estimation methods can be characterized as "planning level" or suitable for developing a small set of alternatives to evaluate further. Normally, a more detailed operations analysis would then be undertaken using HCM methods, microsimulation, or both, to more accurately and precisely estimate the impacts of the strategy on all roadway users.

AASHTO Transit Design Guide

AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets* (2014) is intended to provide "a single, comprehensive reference of current practice in the geometric design of transit facilities on streets and highways." This guidebook's toolbox chapters identify when the AASHTO Transit Guide provides recommendations related to transit-supportive roadway strategies (which is relatively often).

APTA Best Practices

The American Public Transportation Association has begun to develop recommended practices on selected transit topics. One such practice that relates to transit-supportive roadway strategies is *Designing Bus Rapid Transit Running Ways* (APTA 2010), which addresses the geometric design of BRT running way alternatives, including busways on exclusive rights-of-way, exclusive bus lanes, and mixed traffic on arterials.

TCRP Publications

Unlike in the traffic engineering profession, most of the transit industry's knowledge of best practices has not been summarized in a small number of key documents. Instead, TCRP publications (http://www.trb.org/Publications/PubsTCRPPublications.aspx) include guidebooks, such as this one, that present best practices on focused topics of interest to the transit industry.

Transit Agency Design Manuals

Larger transit agencies frequently develop design manuals or guidelines that describe their preferences for designing transit facilities. Some also describe the conditions when typically undesired roadway features (e.g., bus pullouts, speed humps) might be considered or when transit-supportive roadway strategies might be considered. Bus dimensions specific to the transit agency's current bus fleet are a key feature of these manuals for transportation engineers to be aware of. These are used when designing roadways and off-street facilities to accommodate buses. Buses are becoming less standardized, and standard bus templates, such as those provided in the Green Book (AASHTO 2011), may not be suitable for a particular transit agency's fleet.

APPENDIX C

Managing Bus and Bicycle Interactions

C.1 Introduction

Streets used by transit vehicles frequently make desirable corridors for bicycle traffic since these roadways often provide direct access to destinations with relatively few stops required. Given the limited amount of street right-of-way that is often available, a challenge can arise in allocating the right-of-way among the various modes (e.g., transit, bicycle, automobile, pedestrian) using the street. The need to serve bicycle traffic may constrain the options available for implementing transit-supportive roadway strategies. Therefore, this appendix provides potential solutions for accommodating both bicycles and buses on streets and at bus stops that are to the benefit of both modes.

C.2 Bus and Bicycle Facility Types

A number of options are available for on-street bus and bicycle facilities; examples are illustrated in Figure C-1. These options can be categorized by the degree of bus separation from automobile traffic and by the degree of bicycle separation from motor vehicle traffic (including buses).

Shared Mixed-Use Lane

With a shared mixed-use lane (Figure C-1a), the right traffic lane is shared by buses, other motor vehicles, and bicycles. Buses are slowed by the other users of the lane and may need to use the adjacent lane (when available) to safely pass bicycles. Bus stops can either be offline (i.e., the bus pulls out of the traffic lane into the parking lane or a bus pullout to stop) or online (i.e., no parking lane exists or a curb extension is provided at bus stops). In the case of offline stops, potential conflicts arise between buses and bicycles as buses maneuver in and out of the stop, buses must wait for a gap in both bicycle and automobile traffic when exiting the stop, and bicycles can generally continue in a straight line past a stopped bus. In the case of online stops, buses stop in the traffic lane (minimizing bus delays when leaving the stop), while other traffic, including bicycles, must either wait behind the bus or (if possible) pass the bus using the adjacent lane.

Shared Bus and Bicycle Lane

Shared bus and bicycle lanes (Figure C-1b) have been used where it is desired to benefit both bus and bicycle traffic, but right-of-way constraints prevent developing separate bus and bicycle facilities. Buses travel more quickly than in a mixed-traffic environment, while bicyclists are provided with some separation from general traffic (Hillsman et al. 2012). Allowing bicyclists to use the bus lane (1) may generate broader support for developing a bus lane by increasing the number of stakeholders that benefit from the lanes and (2) may, particularly when bus service is

(a) Shared mixed-use lane (Albuquerque)

(b) Shared bus and bicycle lane (Austin)

(c) Separate bicycle lane (Washington, D.C.)

(d) Separate bus and bicycle lanes (Austin)

(e) Left-side bicycle lane (New York)

(f) Raised bicycle lane at transit stop (Portland)

Figure C-1. Examples of options for accommodating bus and bicycle traffic.

relatively infrequent, help reduce the perception that the lane is not being used efficiently. Buses and bicycles interact similarly to what occurs in shared mixed-use lanes.

Separate Bicycle Lane

In a separate bicycle lane (Figure C-1c), bicyclists are provided with their own lane, while buses share a lane with general traffic. When the bicycle lane is adjacent to the curb, buses stop in the bicycle lane to serve passengers, which causes bicyclists to wait behind the bus or, more commonly, to go around the bus by merging left into the general traffic lane, thereby creating potential conflicts with other vehicles, including with buses reentering the general traffic lane. When on-street parking is provided to the right of the bicycle lane, buses must weave across the bicycle lane to enter and exit the bus stops created in the parking lane, creating potential conflict points with bicycles, but typically allowing bicyclists to remain in the bicycle facility. When the bicycle lane is located between the curb and a parking lane (e.g., a buffered bicycle lane), it may be possible to raise the bicycle lane to sidewalk level at bus stops (as discussed in the Diverted Bicycle Lane section), eliminating bicycle–vehicle conflicts at bus stops but introducing potential bicycle–pedestrian conflicts. The width used by the parking lane and buffered bicycle lane could also become a shared bus and bicycle lane at the bus stop.

Separate Bus and Bicycle Lanes

Where right-of-way permits, it may be possible to provide separate bus and bicycle lanes (Figure C-1d). Although buses need to pull into the bicycle lane at bus stops, sufficient space is provided to allow bicycles to go around buses without having to merge into the general traffic lane, reducing the number of conflicts relative to the case where no bus lane is provided, but still forcing bicyclists to maneuver out of their desired travel path. Except when bus volumes are high enough that bicyclists are frequently passed by buses, the bus lane serves as a buffer between bicyclists and motor vehicles. If sufficient space is available, it may be possible to raise the bicycle lane to sidewalk level at bus stops (as discussed in the Diverted Bicycle Lane section), eliminating bicycle–bus conflicts at bus stops but introducing potential bicycle–pedestrian conflicts.

Left-Side Bicycle Lane

On one-way streets, an additional option for providing separate bus and bicycle lanes is to locate the bus lane on the right side of the street and the bicycle lane on the left side of the street (Figure C-1e). This arrangement eliminates bicycle–bus conflicts at bus stops and can also reduce the dooring risk for bicyclists since passenger-side car doors are opened less frequently than driver-side doors. Additional signs and pavement markings may be required to highlight to motorists where to expect bicyclists (NACTO 2012).

Diverted Bicycle Lane at Bus Stops

Where space permits, an option for preventing bicycle–vehicle conflicts at bus stops is to divert the bicycle lane around the bus stop, either at its original grade or by raising the bicycle lane to sidewalk level in the vicinity of the bus stop (Figure C-1f). Sufficient space needs to be provided for the ADA-required clear area for bus boarding and alighting, and an ADA-compliant pedestrian access route needs to connect the stop to the sidewalk. Potential bicycle–pedestrian conflicts (e.g., conflicts arising from pedestrians crossing the bicycle lane or queuing in the bicycle lane while waiting for the bus) also need to be addressed. Nevertheless, this treatment can be an effective way to minimize conflicts and delays for both buses and bicyclists.

C.3 Implementation Examples

There are many implementations of bus-only lanes and bicycle-only lanes around the United States. This section focuses on implementations of the less-common methods of accommodating bus and bicycle traffic that have been identified in the literature.

Shared Bus and Bicycle Lane

Hillsman et al. (2012) identified 27 roadways where shared bus and bicycle lanes were being used in the United States as of 2012, plus additional examples of lanes that were being proposed at the time of the research or that had been removed. They also identified examples internationally in Vienna, Austria; Ghent, Belgium; Ottawa, Toronto, and Vancouver, Canada; Paris, France;

170 A Guidebook on Transit-Supportive Roadway Strategies

Geneva, Switzerland; and Edinburgh and London, United Kingdom. The authors categorized shared bus and bicycle lanes as follows: (1) short segments generally less than 0.5 mile long that have constrained right-of-way (e.g., bridges) and serve to connect or extend bicycle facilities; (2) urban segments that are generally less than 2 miles long and are typically located on key commuter routes to downtowns; and (3) suburban/low-density segments that are generally more than 2 miles long and are typically located on high-volume arterial roadways.

Left-Side Bicycle Lane

New York City implemented left-side bicycle lanes on 1st and 2nd Avenues in Manhattan in conjunction with right-side bus lanes as part of their Select Bus Service program (New York City DOT and MTA-NYCT 2011). Portland, Oregon, uses left-side bicycle lanes on a portion of the 5th Avenue transit mall in conjunction with right-side bus and light rail lanes. Philadelphia (Walnut Street), Chicago (Dearborn Street), and Denver (15th Street) have implemented left-side bicycle lanes on streets with frequent bus service but have not installed bus lanes. NACTO (2012) identifies 11 other cities that have installed left-side bicycle lanes but does not state whether these streets have relatively high bus volumes or whether the lanes were installed for other reasons (e.g., to facilitate bicycle turning movements or to minimize driveway or parking conflicts).

Diverted Bicycle Lane at Bus Stops

Portland, Oregon, uses raised bicycle lanes at streetcar stops on NW Lovejoy Street and SW 5th Avenue; one reason for installing this treatment was to avoid forcing bicyclists to cross the streetcar tracks twice at a shallow angle when passing stopped streetcars, which entails a risk of having one's bicycle wheel get caught in the gap adjacent to the rails. Winnipeg, Canada, installed a raised bicycle lane as a pilot project at a bus stop on Pembina Highway. An evaluation of the design (Suderman and Redmond 2013) found that it generally worked well. Although cyclists usually had to maneuver around pedestrians standing in or crossing the raised portion of the bicycle lane (marked only by a parallel set of bricks creating a stripe effect), they did not have to stop. Snow clearing was a challenge since the snow ridges (windrows) created by snowplows blocked access from the at-grade bicycle lane to the raised bicycle lane and vice versa. (This is a potential issue at any location where a raised cycle track begins or ends.) Raised cycle tracks are commonly used in Denmark, where the preferred treatment is to divert them around bus stops whenever space permits; otherwise, bicyclists are required to stop for passengers who are boarding from and alighting onto the cycle track (Andersen et al. 2012). (Note the boarding islands used in Denmark are frequently narrower than what the ADA would permit in the United States.) An at-grade cycle track on Guadalupe Street in Austin, Texas, is diverted at grade around a bus stop at West 21st Street, and examples of diverted bicycle lanes can also be found in Seattle, Washington (e.g., Dexter Avenue).

C.4 Existing Implementation Guidance

United States

AASHTO Transit Design Guide

AASHTO's Transit Guide (2014) acknowledges the potential trade-offs between bus and bicycle facilities in its policy context section (Section 5.1.1.2.3). It notes that bicycles using an exclusive bus lane may sometimes restrict bus speeds to that of bicycles, that bicycle–bus conflicts may occur at bus stops when a bicycle lane is provided to the right of a bus lane, and that bicycle–bus and bicycle–vehicle conflicts may occur when a bicycle lane is provided between a bus lane and a general traffic lane.

The guide identifies high bicycle volumes as a condition that would not support installing curb extensions (Section 5.2.2.2.1). The guide notes that if curb extensions are provided, the bicycle facility might need to be routed around the bus stop, which could create bicycle–pedestrian or bicycle–motor vehicle conflicts.

In the section on bus operation in mixed traffic (Section 5.3.1), the guide states that bicycles and buses can share streets that have bicycle lanes, wide curb lanes, or paved shoulders with few or no conflicts. In these cases, "bicycles can maneuver around a stopped bus with little difficulty," although the difficulty increases as the number of buses increases or bus stop spacing decreases. Bus pullouts are suggested as a means for minimizing bicycle–bus conflicts and allowing bicyclists to remain in their facility at bus stops. The guide states that, due to the increased discomfort caused to bicyclists and bus operators and the reduction in the lane's operational efficiency, it may not be possible to accommodate shared bus and bicycle traffic on high-speed roadways unless adequately wide bicycle facilities are provided.

Finally, the guide identifies 11 ft as the minimum width for a bus lane, with 12 and 13 ft identified as preferable and desirable widths, and states that bus lanes should be wider than these dimensions when shared with bicycles. The guide refers readers to AASHTO's bicycle guide (2012) for recommended widths for lanes shared by buses and bicycles (Section 5.5.2.1); as noted in the following, the bicycle guide provides general guidance on shared-lane widths but no guidance on shared-lane widths specific to buses.

AASHTO Bicycle Design Guide

AASHTO's bicycle guide (2012) includes sections on integrating bicycles with transit (Section 2.7) and shared lanes (Section 4.3). The guide describes the "leapfrog effect" as a primary operating issue when bicycles and buses share the same lane, with bicycles passing buses at bus stops and buses then re-passing bicycles on the way to the next stop. However, research for the Florida DOT on shared bus and bicycle lanes (Hillsman et al. 2012) did not find support for the leapfrog effect, except perhaps on one higher-speed roadway that was studied. The Florida report documented that during 36 h of videotaping at three locations by a study in Minneapolis of a shared bus and bicycle lane, 21 passing maneuvers (bicycles passing buses or buses passing bicycles) were observed. The Florida report speculates that bus drivers and bicyclists adjust their speeds to minimize the need to pass.

The AASHTO bicycle guide identifies "effective countermeasures" for leapfrogging that include providing "proper pavement markings for bike lanes at bus stops," left-side bicycle lanes, combined bus and bicycle lanes, extra training for bus drivers, and educational materials for bicyclists (which could possibly be posted on the side or back of a bus).

With regard to lane widths for lanes shared by bicycles and motor vehicle traffic in general, the AASHTO bicycle guide identifies 14 ft as the minimum width that allows motorists to safely pass bicyclists without encroaching into the adjacent traffic lane, with the usable lane width measured as either (1) center of edge line to center of lane line or (2) gutter longitudinal joint to center of lane line. AASHTO recommends 15 ft for a shared-lane width on steep grades or when on-street parking or drainage grates reduce the usable lane width. AASHTO cautions that shared-lane widths greater than 16 ft may promote side-by-side automobile driving, increased heavy vehicle use, higher motor vehicle speeds, or a combination of these, and recommends that separate bicycle lanes or facilities be provided when width permits.

The AASHTO bicycle guide recommends considering shared-lane markings for bicycles in the following situations related to buses: (1) when lanes are too narrow for side-by-side motor vehicle and bicycle operation and (2) at transit stops to provide guidance to both bicyclists and bus drivers. Shared-lane markings are not recommended when roadway speeds are greater than 35 mph.

Manual on Uniform Traffic Control Devices

The MUTCD (FHWA 2009) provides guidance on signing and marking bus lanes (Sections 2G and 3D, respectively) and on signing and marking bicycle facilities (Sections 9B and 9C, respectively) but does not provide guidance on signing shared bus and bicycle lanes. As part of a study for the Florida DOT, Hillsman et al. (2012) asked the FHWA for guidance on signing such lanes and were provided with this guidance:

- The lane can be marked and signed for buses and bicycles only (with the option to allow right turns at intersections). In this case, bicycle shared-lane markings (sharrows) should not be used as the lane is designated as an exclusive bicycle facility.
- The lane can be marked and signed for buses only (with the option to allow right turns at intersections). In this case, bicycle shared-lane markings may be used to indicate that bicycles are allowed to use the lane; this message can be reinforced with a modified R4-11 sign that reads "Bikes May Use Bus Lane." The shared-lane markings may also be used to guide bicyclists to the left side of the lane at bus stops and intersections.
- Advisory bicycle lane markings—dashed lines and bicycle lane signs indicating a reserved space for bicycles that vehicles can enter when necessary—are a treatment that has been used internationally but would require FHWA experimentation approval for use in the United States.

At locations where a bicycle facility is diverted around the bus stop, the "Bikes Yield to Peds" sign (R9-6) could be used to give priority to persons crossing the bicycle facility to get to or from a boarding island.

Americans with Disabilities Act

The U.S. Department of Transportation has adopted standards for transportation facilities that implement the requirements of the Americans with Disabilities Act. Section 810 of the standards address bus stops (U.S. Access Board 2006). A relevant provision when considering altering a bus stop to provide a raised bicycle lane is that the bus boarding and alighting area should provide a clear length of 96 in. This suggests that boarding islands would need to provide at least 8 ft of clear space between the outer curb and the bicycle facility, and more if the bicycle facility was at grade and a curb ramp was required to take the accessible route to and from the stop across the bicycle facility.

The U.S. Access Board's *Proposed Guidelines for Pedestrian Facilities in the Public Right-of-Way* (2011) repeats the requirement for a clear length of 8 ft (section R308) and adds a new requirement for detectable warning surfaces (i.e., truncated domes) along the platform edge adjacent to the street. The Access Board's discussion (2013) on a proposed supplement to the public right-of-way guidelines for shared-use paths indicates that it is considering including a requirement in the final regulations to provide detectable warning surfaces "where a shared use path intersects another shared use path or a sidewalk to indicate the boundaries where bicyclists may be crossing the intersection," with such surfaces to be installed within 6 to 12 in. of the edge of the intersecting paths and extending "2 feet minimum in the direction of pedestrian travel and the full width of the intersecting segments." This requirement, if adopted, would likely require detectable warning surfaces on either side of the raised bicycle lane for the length of the boarding island on the side opposite the street.

NACTO Urban Bikeway Design Guide

The National Association of City Transportation Officials' general guidance relating to bicycle facilities in the vicinity of bus stops is that "special consideration should be given at transit stops to manage bicycle and pedestrian interactions" (NACTO 2012).

The section of the NACTO guide on one-way protected cycle tracks includes an illustration of a treatment that wraps an at-grade bicycle facility around a bus boarding island. Curb ramps facilitate wheelchair access between the sidewalk and boarding island; crosswalk markings are shown at this crossing point, along with yield symbol markings across the bicycle facility to indicate that bicyclists should yield. The NACTO illustration also shows the potential for pedestrian access via a ramped walkway, located between the general traffic lane and the bicycle lane, that connects the intersection crosswalk to the boarding island.

The section of the NACTO guide on raised cycle tracks indicates the need for "color, pavement markings, textured surfaces, landscaping, or other furnishings to discourage pedestrian use of the cycle zone" when the cycle track is at sidewalk height.

NACTO's design guidance for cycle tracks on intersection approaches also provides relevant guidance for bus stops:

- Use a maximum 1:8 slope (i.e., 12.5%) when lowering a bicycle facility to grade.
- Avoid sharp changes in direction.
- To improve bicyclist visibility, prohibit parking 30 to 50 ft in advance of an intersection.
- When it is possible to install bicycle signals at an intersection, consider raising the cycle track to sidewalk level and wrapping the facility around the bus stop; bicycles would yield to pedestrians in this case.
- When bicycle signals are not provided, develop an extended mixing zone at the bus stop. A sign should direct bicyclists to yield to buses and pedestrians.

NCHRP Report 672

NCHRP Report 672: Roundabouts: An Informational Guide, 2nd Edition (Rodegerdts et al. 2010) provides guidance in Section 6.8.2.2 on raising bicycle lanes to sidewalk level on an approach to a roundabout; this guidance could also be relevant to raising bicycle lanes at bus stops. The report suggests placing the ramp within the landscaping area, if possible, and orienting the ramp at a 35° to 45° angle to the sidewalk to slow bicyclists down. Similarly, the report suggests that a grade of up to 20% could be used to slow bicyclists down. At exit points, a shallower ramp angle (e.g., 20°) could be used since slowing down bicyclists is not an issue, but "some angle is necessary so that blind pedestrians do not inadvertently travel down the ramp." The report also indicates that detectable warning surfaces are required at the top of the ramp to warn visually impaired pedestrians. Finally, bicyclists can be given the option to bypass the ramp (traveling through the roundabout as a vehicle) or to use the ramp (traveling through the roundabout as a pedestrian or shared-use path user).

The Netherlands

The *Design Manual for Bicycle Traffic* (CROW 2007) provides some guidance on designing for bicycle and bus interactions. The manual provides minimum widths for the following dimensions, among others: shy distance between a bicyclist and a curb (0.25 m) [0.8 ft], width used by an individual bicyclist (0.75 m) [2.5 ft], shy distance between one bicyclist passing another (0.5 m) [1.6 ft], and shy distance between a vehicle and a bicyclist (0.85 m) [2.8 ft]. The manual states that "almost all motorized traffic will overtake bicycle traffic" when the available road space accommodates the width of the car plus an 0.85 m or greater separation from the bicyclist. If the available separation is less than 0.85 m, some motorists will try to pass anyway, while others will remain behind the bicyclist, "which leads to a dangerous, unwanted situation."

The manual identifies four combinations of roadway functional classifications for motor vehicles (corresponding to local and collector/arterial) and bicycles (main cycle route and other routes).

The manual recommends separating bicycle and bus traffic on collector/arterial roadways and preferably separating them on local roadways that serve as main cycle routes. No separation is necessary or desirable on local roads that are not main cycle routes. More specifically, the manual recommends separating bus and bicycle traffic when bus speeds exceed 30 km/h (20 mph).

The manual states that "cyclists may be permitted to ride on bus lane carriageways if they have their own separate lane," and that bike lanes should not be placed between the bus lane and a general traffic lane. The minimum recommended width for the combination of a bus-only lane and bicycle lane is 4.60 m (15 ft), increasing to 5.00 m (16.5 ft) if driving speeds exceed 50 km/h (30 mph).

The manual recommends that buses stop off the roadway (i.e., in a pullout) when they would otherwise need to stop in a bicycle lane. The conflict involved with crossing the bicycle lane is judged to be "not serious and hence acceptable." Pullouts should be designed so that no part of the bus blocks the bicycle lane. When raised cycle tracks are provided, the manual recommends curving them around the bus stop.

Denmark

The *Collection of Cycle Concepts* (Andersen et al. 2012) discusses bicycle and bus interactions at bus stops at several points. In terms of bus stop location, in order to avoid bicycle–car conflicts caused by bicyclists weaving around stopped buses, the guide recommends using bus pullouts when buses would have to stop in a bicycle lane. In this case, the bicycle lane striping should be dashed, and bicycle symbols should be placed at the bicycle–bus conflict points. Alternatively, the bicycle lane can be raised and routed around the bus stop. When bicycle lanes are buffered by a row for parking, the space used for parking can be used for a boarding platform at bus stops.

Raised cycle tracks between the travel lane and the sidewalk are a common bicycle facility type in Denmark but have problems in space-constrained locations where bus passengers must board and alight from the cycle track because bicyclists do not always yield to pedestrians as they should. Pedestrian crossing markings on cycle tracks at these locations have been shown to reduce bicycle speeds noticeably but are no longer allowed by Danish road standards (as they lead pedestrians into the street when a bus is not present). A technological solution in which crosswalk markings would be projected onto the cycle track when a bus is present may be tested in the future.

The guide recommends setting back bus stops at least 20 m (65 ft) from intersections since stopped buses block motorists' views of bicyclists. The guide also recommends never placing bus stops right at the stop bar at intersections because a line of stopped bicyclists can block buses trying to access the stop. According to the guide, far-side stops work best for both buses and bicyclists.

C.5 Discussion

Overview

Managing bicycle–bus interactions at bus stops can result in efficient operations for buses and bicyclists. Redesigning a roadway to provide bus preferential treatments and bicycle accommodations can help build support for a bus-focused project by increasing the number of stakeholders benefiting from the project. In jurisdictions requiring bicycle facilities to be incorporated into new or upgraded roadway projects, finding a way to safely accommodate bicycles may influence whether the desired bus preferential treatment can be constructed. In all cases, incorporating bicycle considerations into a project reflects a Complete Streets approach in which a roadway functions well for users of many different travel modes.

Lane Width

There is a consensus in the literature that the width provided to buses and bicycles plays a role in determining how safely the two modes interact as well as the quality of service provided to each mode. In addition, higher motor vehicle speeds and higher bicycle or bus volumes suggest the need for greater separation.

Hillsman et al. (2012) calculated the minimum width required for a shared bus and bicycle lane to ensure "safety and satisfactory level of service for all roadway users." Their calculated width of 16 ft, 7 in. included 3 ft, 4 in. of bicycle operating space and shy distance to the curb, 3 ft of clearance between a motor vehicle and a bicycle (required by law in Florida and a number of other jurisdictions), 8 ft, 6 in. width for a standard transit bus, and 1 ft, 9 in. clearance to the left edge of the lane (placing the bus within the middle of the leftmost 12 ft of the lane). With this width, buses would not need to move sideways in the lane when passing bicyclists yet an adequate buffer between buses and bicycles would be maintained.

Hillsman et al. (2012) also inventoried the actual widths of shared bus and bicycle lanes constructed in the United States, which ranged from 9 to 16 ft, with the width of a number of facilities varying along their length. The total width of constructed adjacent bus and bicycle lanes ranged from 15 to 20 ft. The researchers also inventoried roadway agency standards for shared and adjacent bus and bicycle lanes but found few formal standards. Among the four U.S. cities they identified with standards for shared bus and bicycle lanes, three used 10 ft to either 12 or 13 ft as a standard; the fourth used 12 ft as a minimum width and 18 ft as a preferred width. Two U.S. cities used 14 to 17 ft as the standard for adjacent bus and bicycle lanes.

The lower end of these shared bus and bicycle lane widths identified (e.g., 10 to 13 ft) roughly correspond to AASHTO's (2014) guidance for bus lane widths (11 to 13 ft). A shared bus and bicycle lane with a width under 16 ft would require buses to use the adjacent lane (if available) to pass bicycles. This is based on 1.5-ft curb-and-gutter width, 3-ft minimum bicycle operating space, 3-ft clearance between bus and bicycle, and 8.5-ft bus width. However, as 16 ft also represents the total of AASHTO's minimum bus lane width (11 ft) and NACTO's (2012) minimum bicycle lane width (5 ft), providing separate bus and bicycle facilities would seem to be preferable to providing a shared lane of the same width, unless local standards prescribed wider minimum widths (e.g., 12-ft bus lanes or 6-ft bicycle lanes). A bicycle passing a stopped bus would require a minimum of 14.5 ft of width to avoid entering the adjacent lane (8.5-ft bus width, 3-ft clearance, 3-ft bicycle operating space).

Shared Versus Adjacent Bus and Bicycle Lanes

AASHTO (2014) does not provide minimum bus volumes for installing a bus lane but notes that "peak hour one-way bus volumes of about 40 to 75 buses will provide a bus presence without creating excessive bunches." NACTO's (2012) guidance indicates that bicycle lanes "are most helpful" (1) when the speed limit is at least 25 mph, (2) on streets with large numbers of buses, and (3) on streets where the motorized vehicle average daily traffic is 3,000 or greater.

Based on the NACTO guidance, bicycle lanes or other dedicated bicycle facilities would be preferred in most situations where a bus lane might be considered and bicycle traffic needs to be accommodated. Situations where a shared lane might be considered are (1) business districts with speed limits of 20 mph, (2) bus lanes that would be used by a low volume of buses and a low-to-moderate volume of bicycles (to improve perceptions that the lane is being used), and (3) locations with insufficient right-of-way to accommodate bus and bicycle traffic in separate facilities. In the latter case, unless it is possible to route bicycles around bus stops, short sections of a shared lane without bus stops would operate better for both buses and bicycles compared to frequently spaced stops across longer sections.

Roadways with significant uphill grades would not be good candidates for relatively narrow shared lanes because the speed differential between bicycles and buses would be considerably greater, and buses would experience greater delay in situations where they could not immediately pass bicyclists compared to level or downhill roadway sections. Roadways with a high volume of traffic in the adjacent lane are also not good candidates for relatively narrow shared lanes since buses would frequently have to slow behind bicyclists while waiting for a gap in traffic to move around the bicyclist and because bicyclists must pass stopped buses.

Buffered bicycle lanes or raised cycle tracks are potential solutions when it is desired to maintain on-street parking. The parking lane would be placed between the bicycle lane and the bus lane and would be replaced with a boarding island at bus stops. Bicycle–bus conflicts would be eliminated, potential conflicts between car doors and bicycles would be reduced, and bicyclists would be buffered from moving motor vehicle traffic.

Managing Bicycle–Bus Conflicts at Bus Stops

Diverted Bicycle Lane at Bus Stops

Where space permits, a diverted bicycle lane is an option for midblock and far-side bus stops for managing bicycle–bus conflicts. (They are more challenging to install at near-side stops at the intersection since there is typically insufficient length available to transition the bicycle facility back into the street, and pedestrian–bicycle interactions at street corners have to be carefully managed.) The required space could be created from space used for landscaping or street furniture elsewhere along the block face or from the space used by on-street parking.

A minimum of 8 ft of width would be required between the curb and the bicycle lane to meet ADA standards (at least at the location where the ADA pedestrian access route to and from the bus stop would cross the bicycle lane). More width may be required if (1) the bicycle lane is at a lower grade than the bus stop platform, thus requiring curb ramps at the point the pedestrian access route crosses the bicycle lane, or (2) the number of waiting passengers that need to be accommodated on the bus stop platform creates the need for more waiting area. The *Transit Capacity and Quality of Service Manual* (Kittelson & Associates et al. 2013) provides methods for estimating the required platform area given the number of passengers to be designed for. San Francisco's accessible bicycle facility guidelines (SFMTA 2014) provide an example of raising the bicycle lane to the platform grade at the location of the ADA pedestrian access route.

The literature generally agrees that it is necessary to manage bicycle–pedestrian conflicts when diverted bicycle lanes are used at bus stops, but it does not agree on the methods that should be used. European practice and NACTO suggest a shallower angle and, when the bicycle lane is raised, gentler slopes when diverting a bicycle facility around a bus stop; this approach allows bicyclists to maintain their speeds since conflicts may be minimal whenever buses are not actively loading and unloading passengers. A Canadian implementation and U.S. roundabout practice suggest a sharper angle and a steeper slope to force bicyclists to slow down. The Canadian implementation (Suderman and Redmond 2013) used a 20° angle and a 5% slope, narrowed the bicycle facility from approximately 6 ft to approximately 4 ft, and introduced a rumble strip on the bicycle facility. The MUTCD provides or is expected to provide in the next edition guidance on colored pavement, bicycle markings, and "Bikes Yield to Peds" signs. Conflicts may arise between bicyclists and sight-impaired pedestrians who cannot see or hear bicyclists approaching, and in the future, regulations implementing the ADA may require detectable warning surfaces separating the bicycle facility from both the sidewalk and the bus stop.

Clearly there is an opportunity for more research on the design of diverted bicycle lanes at bus stops; ultimately, the design selected may depend on the relative volumes of buses, bicycles, and passengers using the stop, bus and general traffic speeds, and the design of the bicycle facility (i.e., shared, adjacent to the travel lane, or buffered). If the number of buses using the stop is relatively low, bicyclists could ride through the bus stop most of the time since no buses would be present. However, as the number of buses stopping increases and the number of passengers boarding or alighting a given bus increases (thus increasing bus dwell time), the probability that a bus will interfere with a bicyclist will increase, and the benefit of separating bicyclists from buses will also increase.

The leftmost diagram in Figure C-2 uses elements identified in the literature to illustrate a design concept for a bus stop with a raised bicycle lane. (All of the diagrams in Figure C-2 illustrate only the portion of the street serving one direction of travel. For ease of presenting the basic design elements, a midblock stop is depicted.) In this concept, the basic street cross-section includes a 6-ft bicycle lane and a 6-ft landscape buffer. At the bus stop, the bicycle lane is diverted out of the street at a 20° angle, raised to sidewalk level, and narrowed to 4 ft wide, leaving 8 ft of width for the boarding area. A “Bikes Yield to Peds” sign is provided near the start of the ramp. Paint or contrasting pavement color is used to designate the bicycle lane. After the stop, the bicycle lane is lowered and angled back to its original alignment. Not shown, but potentially required, are detectable warning surfaces along the edge of the raised bicycle lane. A rumble-strip treatment could also be considered to encourage bicyclists to slow down, but potential pedestrian tripping hazards would need to be addressed. Local laws that prohibit bicycling on sidewalks might require changing to allow a raised bicycle lane configuration.

An at-grade diverted bicycle lane would be developed similarly but without the changes in bicycle lane grade. The bicycle lane width would need to be wider (e.g., 5 ft) than in the raised case to accommodate shy distance from both curbs, particularly for cargo bicycles and bicycles with trailers. Additional boarding platform width might be required to accommodate curb ramps at the point the pedestrian access route crosses the bicycle lane.

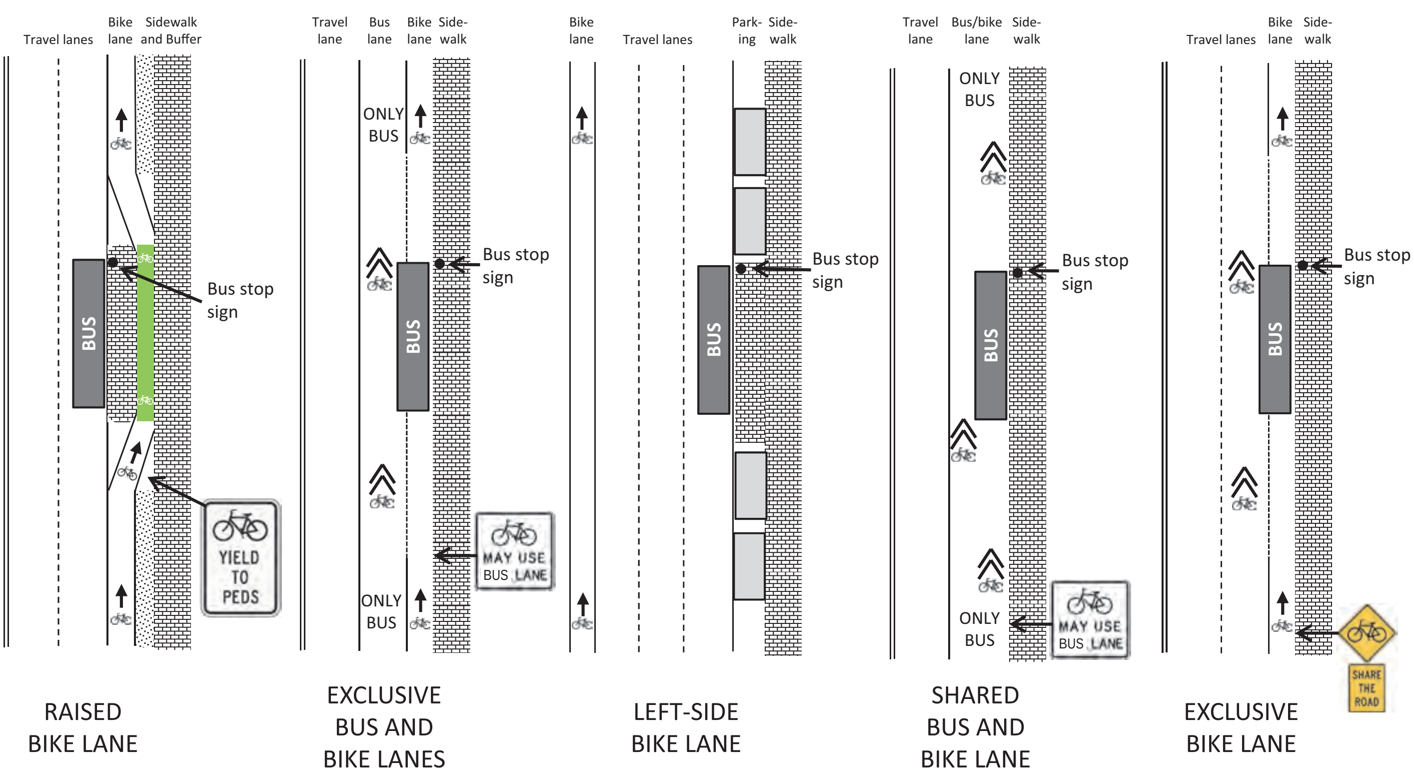


Figure C-2. Illustrative design concepts for accommodating bus and bicycle traffic.

Exclusive Bus and Bicycle Lanes

When space does not permit detouring a bicycle facility around a bus stop, and a bus lane is desired on the street, another option for two-way streets, if sufficient space exists for both facilities, is to provide separate bus and bicycle lanes. This arrangement allows buses to pass bicyclists between bus stops and provides sufficient room for bicyclists to pass stopped buses without having to use a general travel lane. Bicycle–vehicle interactions are limited to buses, which are driven by professional drivers.

The second-to-the-left diagram in Figure C-2 draws from the literature to illustrate a concept for the basic signing and marking features in the vicinity of a bus stop. The bicycle lane marking becomes dotted at the point where a bus would pull over to the curb in advance of the bus stop and remains dotted beyond the stop to a point where a bus would have fully reentered the travel lane (see Figure 9C-6 in the MUTCD for an illustration of bike lane markings near bus stops). A "Bikes May Use Bus Lane" (modified R4-11) sign is placed at the point where buses may enter the bicycle lane. (Local or state traffic laws may need to be updated to allow bicycles to use bus lanes in this manner.) Shared-lane markings (sharrows) are placed at the outside of the exclusive bus lane to indicate to bicyclists where to travel when the bus stop is in use. (This use assumes that the speed limit is 35 mph or less, per MUTCD requirements.) Installing a concrete pad at the bus stop can minimize bus-caused pavement deformation that could negatively affect bicyclists.

Left-Side Bicycle Lanes

The literature is in general agreement that left-side bicycle lanes are a potential treatment for one-way streets since they can provide benefits to buses and bicyclists. Motorists' attention may need to be drawn to the presence of bicyclists on the left side because motorists may not be accustomed to looking for bicyclists there; NACTO (2012) provides guidance on signing and marking left-side bicycle lanes.

The middle diagram in Figure C-2 shows a concept for a one-way street that allows on-street parking on the right side and provides a left-side bicycle lane (which could possibly have on-street parking to its left). The space used by the parking lane is used for a curb extension at the bus stop, allowing buses to stop in the travel lane (reducing bus delay) and providing a waiting area for passengers without disrupting pedestrian flow on the adjacent sidewalk.

Shared Bus and Bicycle Lanes

Where space does not permit providing separate bus and bicycle lanes, and a bus lane is desired to improve bus operations, shared bus and bicycle lanes can be considered. Although the operation of buses and bicycles passing each other still needs to be considered—particularly at bus stops—a Florida study (Hillsman et al. 2012) did not find support for the "leapfrogging" phenomenon raised by AASHTO (2014) as a potential issue. Research is needed in this area. Bicyclists and buses benefit from the reduced amount of traffic using a shared bus and bicycle lane. Wider lanes minimize the need to encroach into the adjacent travel lane when passing.

The second-to-the-right diagram in Figure C-2 draws from the literature to show a concept for a shared bus and bicycle lane in the vicinity of a bus stop. In this concept, the lane is marked as a bus lane, and periodic "Bikes May Use Bus Lane" (modified R4-11) signs are used to indicate that bicycles may also use the lane. (Local or state traffic laws may need to be updated to allow bicycles to use bus lanes in this manner.) To help guide bicyclists with their placement within the lane, shared-lane markings (sharrows) are placed on the right side of the lane between bus stops and on the left side of the lane immediately prior to a bus stop. (Again, this use assumes that the posted speed is 35 mph or less, per MUTCD requirements.) Installing a concrete pad at the bus stop can minimize bus-caused pavement deformation that could negatively affect bicyclists.

Exclusive Bicycle Lanes

Providing an exclusive bicycle lane rather than a shared mixed-use lane avoids the need for buses to change lanes when passing a bicyclist, thus reducing bus delay on streets used by significant numbers of bicyclists. At the same time, bicyclists benefit from the separation from general traffic.

The rightmost diagram in Figure C-2 draws from the literature to show a concept for an exclusive bus lane in the vicinity of a bus stop. Similar to the case of separate exclusive bus and bicycle lanes discussed earlier, the bicycle lane marking becomes dotted at the point where a bus would pull over to the curb in advance of the bus stop and remains dotted beyond the stop to a point where a bus would have fully reentered the travel lane (see Figure 9C-6 in the MUTCD for an illustration of bike lane markings near bus stops). If the street's posted speed is 35 mph or less, shared-lane markings (sharrows) are placed sufficiently far into the adjacent lane in the vicinity of the bus stop that bicyclists have a 3-ft buffer to a stopped bus. A "Bicycle Warning" (W11-1) sign with a "Share the Road" plaque (W16-1P) is installed in advance of the end of the exclusive bicycle lane. The MUTCD states (Section 9B.19.03) that this plaque should be installed at least 50 ft in advance of the condition being warned about; general MUTCD guidance for warning signs (Table 2C-4) would indicate a maximum distance of 100 ft, with consideration given to site conditions and the location of other signs. Installing a concrete pad at the bus stop can minimize bus-caused pavement deformation that could negatively affect bicyclists.

Shared Mixed-Use Lanes

If the roadway is designated as a bicycle route or if the combination of bus and bicycle volumes and dwell times (e.g., a timepoint, a high-volume stop) are high enough that stopped buses would often be passed by bicycles, then a "Bikes May Use Full Lane" (R4-11) or a "Bicycle Warning" (W11-1) sign with a "Share the Road" (W16-1P) plaque could be considered at bus stops along that roadway. If the lane is sufficiently wide and posted speeds are 35 mph or less, then shared-lane markings (sharrows) could also be considered.

Bus Pullouts

Bus pullouts, or bus bays, are not generally desirable from a bus operations standpoint due to the delays buses encounter waiting for a gap in traffic when leaving the pullout. However, they are sometimes needed to reduce the risks of vehicle conflicts—for example, when buses operate on higher-speed roadways (e.g., greater than 40 mph) or due to traffic operations considerations such as the number of vehicles that might be delayed, the length of time they might be delayed, and inability for vehicles to pass a stopped bus (AASHTO 2014).

If a pullout is required, it should allow a bus to stop without blocking the adjacent bicycle lane or shoulder bikeway (if present). If a bicycle lane exists, the lane lines would be dotted in the vicinity of the bus stop to indicate that buses can pass through the lane while entering and exiting the stop. When sufficient right-of-way exists to install a pullout, there may be benefit to routing a bicycle facility (if present) around the pullout to avoid bicycle–bus conflicts when buses are entering and exiting the stop.

C.6 Conclusions

Additional research is needed to better quantify the operational and safety performance of buses, bicycles, and other roadway users associated with the different types of bus stop treatments. In the absence of this research, the literature suggests the following order of preference for accommodating both buses and bicycles at bus stops:

1. Providing a left-side bicycle lane on one-way streets, separating bus and bicycle traffic entirely, with consideration given to calling motorists' attention to the presence of bicyclists, who could be in an unexpected location.

2. Diverting the bicycle facility around the bus stop, with consideration given to managing bicycle–pedestrian conflicts at the stop.
3. Providing separate exclusive bus and bicycle lanes, which eliminates the need for bus–bicycle passing maneuvers between stops and provides sufficient room for bicycles to pass buses at bus stops without having to move into the adjacent general traffic lane.
4. Providing a shared bus and bicycle lane, with wider lanes functioning best. A 16-ft width allows buses to pass bicycles without encroaching on the adjacent lane (but might encourage right-turning vehicles, if allowed in the lane, to pull in front of stopped buses), while a 14.5-ft width allows bicycles to pass buses without encroaching on the adjacent lane. However, widths down to 11 ft (i.e., the minimum recommended bus lane width) still provide better separation between bicycles and general traffic than occurs in a mixed-traffic environment and may be appropriate in situations where bus volumes are relatively low (e.g., less than one every other traffic signal cycle on average) or in downtown environments where blocks are short and buses travel relatively slowly and are unlikely to pass bicyclists. Depending on the volume of bicycles sharing the lane and the width of the lane, buses can retain much of the benefit of having an exclusive bus lane, while bicyclists have a wider buffer between themselves and general traffic than with an exclusive bicycle lane or a mixed-traffic environment. Shared bus and bicycle lanes may also be useful in short, space-constrained sections of roadway without bus stops.
5. Providing an exclusive bicycle lane, with buses operating in mixed traffic. Buses avoid the need to pass bicyclists midblock, while bicyclists are generally separated from general traffic, except when they need to pass buses that are stopped at bus stops.
6. Shared mixed-use lanes using shared-lane markings (sharrows) to guide bicyclists around stopped buses at bus stops and to inform motorists to watch for bicyclists.

The choice of treatment will depend on a number of factors, including right-of-way availability, bus and bicycle volumes, traffic speeds, the type of existing and planned bicycle facility on the roadway, existing traffic laws, applicable local roadway design standards, and available budget. Higher bus volumes and the presence of premium transit services (e.g., bus rapid transit) suggest the need for greater separation of bus traffic from other roadway users, while higher bicycle volumes or the designation of the roadway as a priority bicycle facility suggest the need for greater separation of bicycle traffic from other roadway users.

Bus pullouts are not generally desirable from a bus delay standpoint, but when they are used (e.g., on high-speed roadways or as a result of other safety concerns), they should allow buses to stop without blocking the adjacent bicycle lane or shoulder bikeway (if present).

Installing a concrete pad at the bus stop can minimize bus-caused pavement deformation that could negatively affect bicyclists.

APPENDIX D

Request to Experiment Template

D.1 Introduction

At the time this guidebook was written, colored pavement markings specifically for use in transit-preferential lanes had not been included in the *Manual on Uniform Traffic Control Devices.* Until the FHWA has included colored pavement markings for transit-preferential lanes in the MUTCD, either through interim approval or an update of the MUTCD, agencies planning to install colored pavement markings for transit-preferential lanes must submit a Request to Experiment (RTE) to FHWA.

The following template can be used by agencies planning to submit an RTE prior to installing colored pavement markings for transit-preferential lanes. The template addresses the information outlined in the MUTCD and required by FHWA for an RTE. However, each installation is unique, and agencies should modify the information provided to address their specific applications. Some of the text in this template is borrowed from a successful experimentation request by the City of San Francisco.

Per guidance in Section 1A.10 of the 2009 MUTCD, the official request to FHWA should include a cover letter on agency letterhead. FHWA prefers requests to be submitted electronically through email to MUTCDofficialrequest@dot.gov. The applicable FHWA Division office should be copied.

The flowchart shown in Figure D-1 from the MUTCD webpage outlines the steps and approximate schedule required for obtaining approval. Additional information on the experimentation process can be found at http://mutcd.fhwa.dot.gov/condexper.htm.

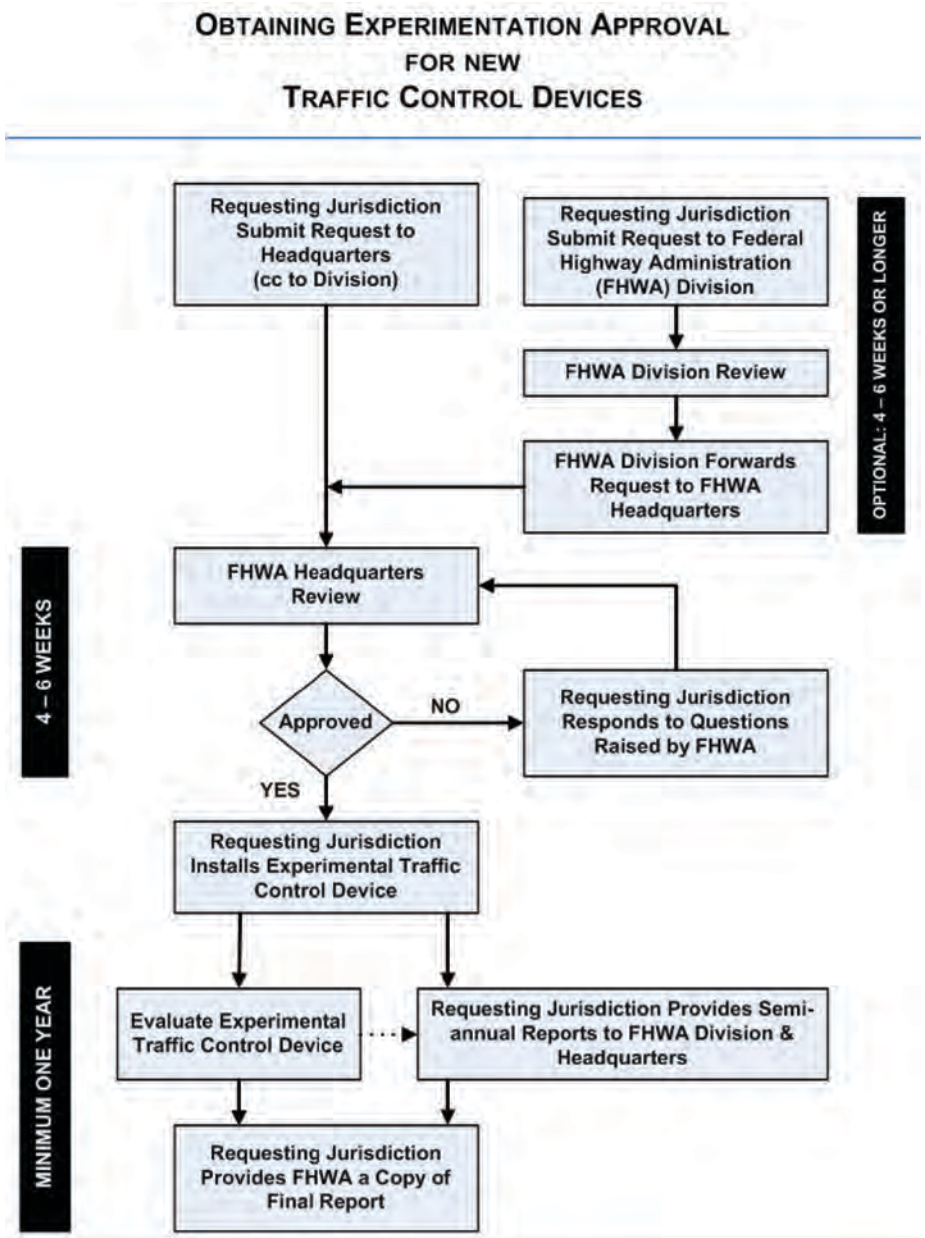
The following typographic conventions are used in the template:

- *Italic red text*—A general description of information required in Paragraph 11 of Section 1A.10 of the 2009 MUTCD provided to guide the user. Delete this text before submitting to FHWA.
- Blue text—Specific guidance describing what should be included in the section. Replace this text with a narrative specific to each experiment being proposed.
- Non-italic red text—This text should be replaced with text specific to the preparing agency.
- Black text—This text is general and should be sufficient for all RTEs with little to no modification.

D.2 Template

DATE

Office of Transportation Operations
Federal Highway Administration
1200 New Jersey Avenue, S.E.
HOTO-1
Washington, DC 20590



Source: FHWA (2009).

Figure D-1. Flowchart for obtaining experimental approval.

RE: Request to experiment with colored pavement markings for transit-preferential lanes in JURISDICTION

AGENCY formally requests approval, as outlined in Section 1A.10 of the Manual on Uniform Traffic Control Devices (MUTCD), to install red-colored pavement markings as an experimental traffic control device for transit-preferential lanes. The proposed device is proposed for implementation at CORRIDOR/INTERSECTION.

This experiment is requested because the use of red-colored pavement markings to mark transit-preferential lanes is currently not allowed in the MUTCD. This experiment will contribute to the body of knowledge regarding colored pavement markings for transit-preferential lanes.

The attached document provides the information and agreements requested in the MUTCD for experimental approval.

We look forward to your review and approval of this request.

Sincerely,

AGENCY

CC: STATE FHWA Division Office

Request to Experiment
Colored Pavement Markings for Transit-Preferential Lanes
CORRIDOR/INTERSECTION

BACKGROUND/NATURE OF THE PROBLEM

A statement of the nature of the problem, including data that justify the need for a new device or application.

Background

This section should describe the agency, project location, and project background.

Nature of the Problem

What is leading to the need to experiment with red-colored transit lanes? The following text is an example and could be used if applicable to your agency's application.

Transit-preferential lanes can reduce transit travel times and improve transit service reliability by allowing transit vehicles to bypass traffic congestion and avoid conflicts with other vehicles in mixed travel lanes. Non-transit vehicles are typically permitted to enter transit-preferential lanes to access curbside parking or to complete a turn unless specifically prohibited. However, non-transit vehicles frequently violate transit-preferential lane restrictions by traveling along or double-parking in transit-preferential lanes. Transit-preferential lane violations can cause transit vehicles to slow down to merge into adjacent lanes or stop to wait for the transit-preferential lane to clear, contributing to longer transit travel times, reduced service reliability, and reduced customer safety and comfort. The intent of this experimentation is to reduce violations of transit-preferential lane restrictions by making existing and future transit-preferential lanes more self-enforcing.

In addition to defining the nature of the problem in narrative form, consider including, either here or in an appendix, the following supporting information:

- Photos showing the existing transit-preferential lane configurations.
- Data (e.g., number of non-transit vehicle violations) that are relevant to the application and justify the need for red-colored transit lanes.

DESCRIPTION OF THE PROPOSED CHANGE

A description of the proposed change, how it was developed, and how it deviates from the current MUTCD.

This section should describe the specific element(s) of the project that deviates from the MUTCD. Include other methods currently in place that have not addressed the problem or alternatives that were considered. Include an assessment of any potentially negative consequences of the installation and how those have been addressed in the design. The following text is an example and could be used if applicable to your agency's application.

AGENCY proposes experimenting with red-colored transit-preferential lanes to determine if they reduce violations of transit-preferential lane restrictions. Transit-preferential lanes in AGENCY/LOCATION generally include pavement messages indicating the class of vehicles permitted to use the lanes (e.g., "Bus Only" and "Bus Taxi Only") and signs indicating when the transit-only regulation is in effect. Some transit-preferential lanes include diamond symbol pavement markings.

The 2009 MUTCD provides guidance for preferential lane word, symbol, and longitudinal markings but does not provide specific guidance for the use of colored transit-preferential lanes. Section 3G.01 of the 2009 MUTCD restricts colored pavement to the colors of yellow and white.

This request for experimentation is for the use of red-colored transit-only lanes as a new traffic control device, including both full-time transit-only lanes and part-time transit-only lanes. AGENCY anticipates that adding red-colored treatments to transit-preferential lanes will improve compliance with existing restrictions.

DIAGRAMS/FIGURES/ILLUSTRATIONS

Any illustration(s) that enhances understanding of the device or its use.

If available, consider including the following information in this section or an appendix:

- Figures showing plans for implementation of the proposed experimentation. Provide relevant engineering details.
- Examples of applications of red-colored pavement markings for transit-only lanes in other jurisdictions.

SUPPORTING DATA/PREVIOUS PRACTICE

Supporting data that explains how the experimental device was developed, if it has been tried, the adequacy of its performance, and the process by which the device was chosen or applied.

Other Requests to Experiment

The following text is an example that could be used without change unless more current information is available.

As of January 2015, at least three agencies had submitted RTEs for experimentation with red-colored pavement for transit-preferential lanes: the City of Chicago, the City of New York, and the San Francisco Municipal Transportation Agency. The New York City DOT has submitted a final report to FHWA for its experimentation. The New York City DOT study evaluated the effect of red treatments on transit travel times, illegal transit lane occupancy by non-transit vehicles, legal parking behavior in lanes with red-colored pavement during non-transit lane hours, and non-transit vehicle right-turning behavior. The New York City DOT study showed positive results but was based on relatively small samples.

Material Details

The following text is an example that could be used without change unless more current information is available.

New York City DOT in conjunction with Penn State University completed an evaluation of nine red transit lane treatment products in 2012. Materials were tested for durability and friction both in the lab and in the field. Field observations of color, susceptibility to dirt and grime, and ease of patching were also conducted, and life-cycle costs were estimated. The evaluation concluded that epoxy-based paints, epoxy/aggregate treatments, and asphalt concrete micro surface treatments provided the best durability. The evaluation also concluded that aggressive pre-treatment of asphalt roadways, including shot-blasting and crack repair, was necessary prior to application of colored treatments to ensure durability.

PATENT/COPYRIGHT PROTECTION

A legally binding statement certifying that the concept of the traffic control device is not protected by a patent or copyright (see MUTCD Section 1A.10 for additional details).

The concept of red-colored pavement markings is not protected by a patent or copyright.

EXPERIMENT TIME PERIOD AND LOCATION

The proposed time period and location(s) of the experiment.

Time Period

AGENCY is requesting the experimental approval start on DATE and end on DATE based on the following schedule.

Activity	Time Period
Material testing, *if applicable*	
Material procurement, *if applicable*	
Before data collection	
Install treatments	
After data collection	
Submit final report to FHWA	

Location

Include a description of the specific location(s) at which the experimental application will be applied. Location information may be described in narrative, tabular, map, and/or another format. The table that follows is an example of a tabular form.

The table that follows provides details for existing and/or proposed transit-only lanes in AGENCY where red-colored pavement may be applied.

Transit-Preferential Lane Location	Time Period of Operation	Type of Operation
Bond Street from Franklin Avenue to Greenwood Avenue	All times	Left-side transit lane adjacent to on-street parking on one-way street
Third Street from Burnside Avenue to Hawthorne Avenue	7 a.m. to 9 a.m. and 4 p.m. to 6 p.m. Monday–Friday	Right-side transit lane adjacent to curb in one direction on two-way street

EVALUATION PLAN

A detailed research or evaluation plan providing for close monitoring of the experimentation, especially in the early stages of field implementation. The evaluation plan should include before-and-after *studies as well as quantitative data enabling a scientifically sound evaluation of the performance of the device.*

This section should describe the proposed evaluation of the red-colored pavement. In determining an appropriate evaluation plan, the first step is to identify the key measures of effectiveness (MOEs) for the device. The example that follows shows candidate MOEs. Your agency may elect to collect different or additional MOEs. The specific evaluation plan, including duration of observation periods, should be structured to obtain a data set that could result in a statistically significant finding. Depending on the specific installation, there may also be related design questions that should be tested, such as the placement of signs and other pavement markings relative to the beginning and end of the red-colored pavement.

The following text is an example that should be modified to be applicable to your agency's application.

AGENCY proposes to evaluate red-colored transit-preferential lanes by collecting before-and-after observational data of transit-preferential lane violations. Each experimental location will be observed using OBSERVATIONAL METHOD (e.g., video, manual observation) during TIME PERIODS.

Before-and-after data to be collected include:

Measure of Effectiveness	Unit of Measure
Traffic counts	Vehicles per hour
Non-transit vehicle travel violations in transit-preferential lane	Vehicles per hour traveling within transit-only lanes, excluding vehicles making legal turning or parking maneuvers
Non-transit parking (or standing vehicle) violations in transit-preferential lane	Parking infractions per hour
Parking occupancy adjacent to transit-only lanes	Percentage of legal parking spaces occupied
Vehicle turning behavior	Turning vehicles per hour per approach lane

In addition to the observational data, the following information may be collected:

- User surveys of motorists, transit vehicle operators, and/or transit customers to collect information on user perceptions of the meaning and effectiveness of the red treatments.
- Before-and-after transit travel times using automatic passenger counters (APCs). The APC units use onboard sensors and GPS to record travel times between transit stops and customer activity at each transit stop.

AGREEMENT TO TERMINATE OR RESTORE

An agreement to restore the experimental site to a condition that complies with the provisions of the MUTCD within 3 months of completion of the experiment. The agreement must also provide that the sponsoring agency will terminate the experiment at any time if it determines that the experiment directly or indirectly causes significant safety hazards. If the experiment demonstrates an improvement, the device or application may remain in place until an official rulemaking action occurs.

Upon request from the FHWA, AGENCY agrees to restore the site of the experiment to a condition that complies with the provisions of the MUTCD within 3 months of completion of the experiment. In the event that the colored pavement markings under experiment directly or indirectly cause significant safety hazards, AGENCY agrees to terminate the experiment and restore the site of the experiment to a condition that complies with the provisions of the

MUTCD. AGENCY and the FHWA acknowledge and agree that if the experiment demonstrates an improvement, the device or application may remain in place until an official rulemaking action occurs.

PROGRESS REPORTING

An agreement to provide semi-annual progress reports for the duration of the experimentation and a copy of the final results to the FHWA's Office of Transportation Operations within 3 months of the conclusion of the experiment.

AGENCY will provide semi-annual progress reports during the course of the experiment and will provide a report documenting the final results within 3 months of the conclusion of the experiment.

PROJECT ADMINISTRATION

AGENCY is responsible for all project administration. The project manager will be:

Name
Title
Agency
Address
City, State ZIP
Phone:
Fax:
Email:

APPENDIX E

Glossary

This glossary contains transit, traffic engineering, and traffic signal terminology used in this guidebook or that might be used during the course of implementing a transit-supportive roadway strategy. Definitions of the strategies used in this guidebook are provided in Section 2.2 and repeated in the individual strategy write-ups in the toolbox chapters (Chapters 5 through 8). Terms in the glossary are derived from the *Transit Capacity and Quality of Service Manual* (Kittelson & Associates et al. 2013), the *Highway Capacity Manual 2010* (Transportation Research Board 2010), and the *NCHRP Report 812: Signal Timing Manual* (Urbanik et al. 2015).

acceleration/deceleration delay—delay experienced by vehicles slowing from and subsequently returning to their running speed.

access point—an intersection, driveway, or opening on either side of a roadway.

active priority—a form of traffic signal priority that adjusts signal timing in reaction to the arrival of a bus.

actuated signal control—phase time based on detection.

adaptive signal control—an advanced signal system that does not operate with time-of-day plans.

alight—to get off or out of a vehicle.

approach—a set of lanes at an intersection that accommodates all left-turn, through, and right-turn movements from a given direction.

arterial roadway—a signalized street that primarily serves through traffic and secondarily provides access to abutting properties.

back of queue—the maximum backward extent of queued vehicles during a typical cycle, as measured from the stop line to the last queued vehicle.

bandwidth—the maximum amount of green time for a designated coordinated movement as it passes through a corridor at an assumed constant speed, typically measured in seconds.

board—to go on to or into a vehicle.

boarding island—a pedestrian refuge within the right-of-way and traffic lanes of a highway or street. It is provided at designated transit stops for the protection of passengers from traffic while they wait for and board or alight from transit vehicles; also known as a pedestrian island, loading island, or safety island.

bunching—a situation where two buses on a route arrive together or at much less than the scheduled headway; followed by a long gap in service.

capacity—the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions.

central business district (CBD)—an area with characteristics such as narrow street rights-of-way, frequent parking maneuvers, vehicle blockages, taxi and bus activity, small-radius turns, limited use of exclusive turn lanes, high pedestrian activity, dense population, and midblock curb cuts.

clock headway—the scheduled headway between transit unit (vehicle or train) trips; based on even times (e.g., 60, 30, 20, 15, 10, and 7½ min).

collector street—a surface street providing land access and traffic circulation within residential, commercial, or industrial areas.

concurrent phases—two or more phases in separate rings that are able to operate together without conflicting movements.

conflict—the crossing, merging, or diverging of two traffic movements at an intersection.

control delay—delay associated with vehicles slowing in advance of an intersection, the time spent stopped on an intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate to their desired speeds.

controller—the piece of hardware that determines how a traffic signal responds to calls based on signal timing parameters.

coordinated phase(s)—the phase (or phases) that are given a fixed minimum amount of time each cycle under a coordinated timing plan. This phase is typically the major through phase on an arterial. A coordinated phase may also have an optional actuated interval following the fixed interval.

curb extension—an extension of the sidewalk into the roadway for passenger loading without the bus pulling into the curb; gives priority to buses and eases reentry into traffic; often landscaped and fitted with a bus shelter and other passenger amenities. At intersections, also shortens pedestrian crossing distances. Also called a bus bulb, bus bulge, bus nub, or curb bulge.

cycle—a complete sequence of signal indications.

cycle failure—a condition where one or more queued vehicles are not able to depart an intersection as a result of insufficient capacity during the cycle in which they arrive.

cycle length—the duration of a complete sequence of phases in the absence of priority calls. In an actuated controller unit, a complete cycle is dependent on the presence of calls for all non-priority phases. Some indications may be served more than once in a cycle. Occasionally, an indication may not be part of a normal cycle (e.g., a left-turn arrow may only be displayed during railroad preemption).

cycle time—the time required for a bus to make a round trip on a route, including layover and schedule recovery time.

delay—additional travel time experienced by a driver, passenger, bicyclist, or pedestrian beyond that required to travel at the desired speed.

demand—the number of vehicles or other roadway users desiring to use a given system element during a specific time period. Not to be confused with volume, which is a measure of how many users are accommodated at an intersection (which is limited to the available capacity).

detector—a device used to count or determine the presence of a motorized vehicle, bicycle, or pedestrian.

display (head, signal group)—a combination of indications (e.g., red, yellow, green, green arrow, audible) grouped together for controlling one or more movements.

double cycle—a cycle length that allows phases at an intersection to be served twice as often as the phases at other intersections in the coordinated system.

downstream—the direction of traffic flow.

dwell time—the sum of the time required to serve passengers at a transit stop and the time required to open and close the vehicle doors.

dwell time variability—the distribution of dwell times at a stop because of fluctuations in passenger demand for buses and routes.

early return to green—a term used to describe the servicing of a coordinated phase in advance of its programmed begin time as a result of unused time from non-coordinated phases.

effective green time—the time during which a given traffic movement (or set of movements) may proceed; it is equal to the cycle length minus the effective red time. In a practical sense, effective green time is equal to actual green time since the start-up lost time is approximately equal to the amount of time during the yellow change interval when vehicles are still entering the intersection.

effective red time—the time during which a given traffic movement (or set of movements) is not moving into the intersection; it is equal to the cycle length minus the effective green time.

far-side stop—a bus stop located beyond an intersection.

flow rate—the equivalent hourly rate at which vehicles or other roadway users pass over a given point or section of a lane or roadway during a given time interval of less than 1 h (usually 15 min).

frequency—the number of transit units (vehicles or trains) on a given route or line, moving in the same direction, that pass a given point within a specified interval of time, usually 1 h.

fully actuated control—a signal operation in which vehicle detectors on each approach to the intersection control the occurrence and length of every phase.

general traffic lane—a lane open to any motorized vehicle.

green time—the duration of the green indication for a given movement at a signalized intersection.

green-time (*g*/*C*) ratio—the ratio of the effective green time of a phase to the cycle length.

headway—the time interval between successive buses in the same direction.

indication—see display (head, signal group).

interval—the duration of time during which traffic signal indications (e.g., red, yellow, green, and flashing "Don't Walk") do not change state (i.e., red interval, yellow interval, green interval, and flashing "Don't Walk" interval).

isolated operation—an intersection that is not currently being operated as part of a coordinated system. Also known as free operation. See also *uncoordinated (free) operation.*

lagging left turn—a left-turn phase that occurs toward the end of service to an intersection approach.

layover time—time built into a bus schedule between trips used for operator rest time and to make up delays from the previous trip. See also *schedule recovery time.*

leading left turn—a left-turn phase that occurs at the start of service to an intersection approach.

leading pedestrian interval—a pedestrian interval option that starts a few seconds before the adjacent through vehicular phase, thus allowing pedestrians to establish a presence in the crosswalk and thereby reducing conflicts with turning vehicles.

level of service (LOS)—a quantitative stratification of a performance measure or measures that represent quality of service; measured on an A through F scale, with LOS A representing the best operating conditions from the traveler's perspective and LOS F the worst.

loading area—a curbside space where a single bus can stop, load, and unload passengers. Bus stops include one or more loading areas.

lost time—the time per signal cycle during which the intersection is effectively not used by any movement; this occurs during the yellow change and red clearance intervals (clearance lost time) and at the beginning of most phases (start-up lost time).

master clock—the background timing mechanism within the controller logic to which each controller is referenced during coordinated operations.

master controller—an optional component of a signal system that facilitates coordination of the signal system with local controllers.

maximum green—the maximum amount of time that a green signal indication can be displayed in the presence of conflicting demand.

median—the area in the middle of a roadway separating opposing traffic flows.

midblock stop—a bus stop located at a point away from intersections.

minimum green—the least amount of time that a green signal indication will be displayed when a signal phase is activated.

mode—a transport category characterized by specific right-of-way, technological, and operational features.

movement—a term used to describe the user (e.g., vehicle or pedestrian) action taken at an intersection (e.g., vehicle turning movement or pedestrian crossing). Two different types of movements are those that have the right-of-way (protected/exclusive) and those that must yield (permitted/permissive), consistent with the rules of the road or the Uniform Vehicle Code.

multimodal—the availability of transportation options using different modes within a system or corridor.

near-side stop—a bus stop located on the approach side of an intersection.

off-peak period (base period)—in transit, the time of day during which vehicle requirements and schedules are not influenced by peak-period passenger volume demands (e.g., between morning and afternoon peak periods). At this time, transit riding is fairly constant and usually moderate in volume when compared with peak-period travel.

offline stop—a bus stop where buses stop outside the travel lane.

offset—the time relationship between the coordinated phase(s) based on the offset reference point and a defined master reference (i.e., master clock or sync pulse).

offset reference point (coordination point)—the defined point that creates an association between a signalized intersection and the master clock.

online stop—a bus stop where buses stop in the travel lane.

overlap—a timing process that provides a way to operate a particular movement with one or more phases. It is a separate output that can use special logic to improve operations.

oversaturated flow—traffic flow where (1) the arrival flow rate exceeds the capacity of a point or segment, (2) a queue created from a prior breakdown of a facility has not yet dissipated, or (3) traffic flow is affected by downstream conditions.

paratransit—forms of transportation services that are more flexible and personalized than conventional fixed-route, fixed-schedule service but not including such exclusory services as charter bus trips. The term paratransit originally referred broadly to categories of service that are public (those that are available to any user who pays a predetermined fare [e.g., taxi, jitney, dial-a-ride]) and semi-public (those that are available only to people of a certain group, such as older adults, employees of a company, or residents of a neighborhood [e.g., vanpools, subscription buses]). However, more recently, paratransit has often been used to refer more specifically to ADA-complementary paratransit.

passive priority—A form of traffic signal priority that is pretimed, such as the setting of a street's signal progression to favor buses.

peak period—(1) The period during which the maximum amount of travel occurs. It may be specified as the morning (a.m.) or afternoon or evening (p.m.) peak. (2) The period when demand for transportation service is heaviest.

pedestrian clear interval—time provided for pedestrians who depart the curb during the "Walk" indication to reach the opposite curb (or the median).

pedestrian phase—time allocated to pedestrian traffic that is typically concurrent with compatible vehicular phase(s).

pedestrian recall—a form of phase recall where the controller places a continuous call for pedestrian service on the phase and then services the phase for at least an amount of time equal to its walk and pedestrian clear intervals (longer if vehicle detections are received).

permitted movement—a movement that is allowed to proceed if there are available gaps in the conflicting flow.

phase—the part of the signal cycle allocated to any combination of traffic movements receiving the right-of-way simultaneously during one or more intervals. A phase includes the green, yellow change, and red clearance intervals.

phase sequence—(1) The sequence of service provided to each traffic movement; (2) A description of the order in which the left-turn movements are served relative to the through movements.

platoon—a group of vehicles or pedestrians traveling together as a group, either voluntarily or involuntarily because of signal control, geometrics, or other factors.

practitioner—a general term for anyone responsible for signal timing, traffic engineering, or transit operation.

pretimed control—a signal control in which the cycle length, phase plan, and phase times are preset to repeat continuously.

progression—the act of various controllers providing specific green indications in accordance with a time schedule to permit continuous operation of groups of vehicles along the street at a planned speed.

protected movement—a movement that has the right-of-way with no conflicting movements occurring.

quality of service—the overall measured or perceived quality of transportation service from the user's or passenger's point of view rather than from the operating agency's point of view.

queue—a line of vehicles, bicycles, or persons waiting to be served due to traffic control, a bottleneck, or other causes.

ramp meter—a traffic signal that controls the entry of vehicles from a ramp onto a limited-access facility; the signal allows one or two vehicles to enter on each green or green flash.

red clearance interval—a brief period of time following the yellow indication during which the signal heads associated with the ending phase and all conflicting phases display a red indication.

red time—the period in the signal cycle during which, for a given phase or lane group, the signal is red.

reentry delay—delay experienced by buses leaving a bus stop when they must wait for a gap in traffic before reentering the travel lane.

reliability—how often transit service is provided as promised; affects waiting time, consistency of passenger arrivals from day to day, total trip time, and loading levels.

ring—a sequence structure consisting of two or more sequentially timed and individually selected conflicting movements arranged to allow flexibility between compatible movements in other rings.

saturation flow rate—the equivalent hourly rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions assuming that the green signal is available at all times and that no lost times are experienced.

schedule recovery time—additional time built into a bus schedule between trips; used when the time potentially required to recover from delays is longer than the layover time.

service span—the number of hours during the day between the start and end of service on a transit route; also known as the hours of service.

signal delay—delay experienced by a bus that arrives at a near-side stop during the green interval, serves its passengers during portions of the green and red intervals, and then must wait for the traffic signal to turn green again before proceeding. See also *control delay.*

signal faces—See display (head, signal group).

speed, running—the highest safe speed at which a vehicle is normally operated on a given roadway or guideway under prevailing traffic and environmental conditions; the speed between points but not including stopped time.

split—the segment of the cycle length allocated to each phase or interval that may occur. In an actuated controller unit, split is the time in the cycle allocated to a phase—the sum of the green, yellow change, and red clearance intervals for a phase.

start-up lost time—the additional time consumed by the first few vehicles in a queue at a signalized intersection, above and beyond the saturation headway, because of the need to react to the initiation of the green phase and to accelerate. See also *lost time.*

time-of-day plans—signal timing plans associated with specific hours of the day (i.e., associated with fluctuations in demand), days of the week, or days during the year (e.g., holidays, seasons).

traffic delay—the component of delay that results when the interaction of vehicles causes drivers to reduce speed below the free-flow speed.

194 A Guidebook on Transit-Supportive Roadway Strategies

transit signal preemption—the transfer of normal operation of a traffic signal to a special control mode serving a transit vehicle.

transit signal priority—adjustments to traffic signal timing to provide more usable green time to transit vehicles. See also *active priority* and *passive priority*.

uncoordinated (free) operation—a traffic signal not operating as part of a coordinated system of intersections. Free operation can be set by time of day.

undersaturated flow—traffic flow where (1) the arrival flow rate is lower than the capacity of a point or segment, (2) no residual queue remains from a prior breakdown of the facility, and (3) traffic flow is unaffected by downstream conditions.

unsignalized intersection—an intersection not controlled by traffic signals.

upstream—the direction from which traffic is flowing.

volume-to-capacity (*v*/*c*) ratio—the ratio of flow rate to capacity.

walk interval—a period of time intended to give pedestrians adequate time to perceive the "Walk" indication and depart the curb before the pedestrian clear interval begins.

yellow change interval—the period of time that a yellow indication is displayed to alert drivers to the impending presentation of a red indication.

yield point—the earliest point in a coordinated signal operation at which the controller can decide to terminate the coordinated phase(s). It is typically followed by one or more permissive periods that allow the controller to yield to non-coordinated phases later in the cycle yet still return to the coordinated phase(s) in time to remain in coordination. Permissives are primarily beneficial during lower traffic volumes and allow non-coordinated phases to be served if they arrive later than the initial yield point.

Acronyms and Abbreviations

ADA—Americans with Disabilities Act
APC—automatic passenger counter
AVL—automatic vehicle location
BRT—bus rapid transit
CBD—central business district
CMF—crash modification factor
COTA—Central Ohio Transit Authority
DART—Dallas Area Rapid Transit
DOT—department of transportation
HCM—Highway Capacity Manual
HSM—Highway Safety Manual
IGA—intergovernmental agreement
g/C ratio—green-time ratio
JTA—Jacksonville Transit Authority
LOS—level of service
LRT—light rail transit
LTD—Lane Transit District
MOE—measure of effectiveness
MOU—memorandum of understanding
MPO—metropolitan planning organization
MTA—Metropolitan Transportation Authority
MTC—Metropolitan Transportation Commission
MUTCD—Manual on Uniform Traffic Control Devices
NACTO—National Association of City Transportation Officials
NYCT—New York City Transit
ROW—right-of-way
RTE—Request to Experiment
SBS—Select Bus Service
SFCTA—San Francisco County Transportation Authority
SFMTA—San Francisco Municipal Transportation Agency
STA—Spokane Transit Authority
TCQSM—Transit Capacity and Quality of Service Manual
TEP—Transit Effectiveness Project
TSP—transit signal priority
UTA—Utah Transit Authority
v/c ratio—volume-to-capacity ratio

References

Active Transportation Alliance. Complete Streets, Complete Networks. Chicago, IL, 2012.

Albright, E. and M. Figliozzi. Factors Influencing Effectiveness of Transit Signal Priority and Late-Bus Recovery at Signalized-Intersection Level. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2311*, 2012, pp. 186–194.

AASHTO. Guide for the Planning, Design, and Operation of Pedestrian Facilities. Washington, D.C., 2004.

AASHTO. *Highway Safety Manual*, 1st Edition. Washington, D.C., 2010.

AASHTO. A Policy on Geometric Design of Highways and Streets, 6th edition. Washington, D.C., 2011.

AASHTO. *Guide for the Development of Bicycle Facilities.* Washington, D.C., 2012.

AASHTO. *Guide for Geometric Design of Transit Facilities on Highways and Streets*. Washington, D.C., July 2014.

Andersen, T., F. Bredal, M. Weinreich, N. Jensen, M. Riisgaard-Dam, and M. K. Nielsen. Collection of Cycle Concepts 2012. Cycling Embassy of Denmark, Copenhagen, 2012.

APTA. *Designing Bus Rapid Transit Running Ways.* Recommended Practice APTA-BTS-BRT-RP-003-10. Washington, D.C., October 2010.

APTA. *2014 Public Transportation Fact Book.* Washington, D.C., November 2014.

BC Transit. Infrastructure Design Guidelines. Victoria, Canada, November 2010.

Beswick, G. Pre-Signals in London Study. Executive Summary. London Transport Buses, London, U.K., 1999.

Boyle, D. K. *TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds.* Transportation Research Board of the National Academies, Washington, D.C., 2013.

Boyle, D. K. *TCRP Synthesis 117: Better On-Street Bus Stops.* Transportation Research Board of the National Academies, Washington, D.C., 2015.

Boyle, D., J. Pappas, P. Boyle, B. Nelson, D. Sharfarz, and H. Benn. *TCRP Report 135: Controlling System Costs: Basic and Advanced Scheduling Manuals and Contemporary Issues in Transit Scheduling.* Transportation Research Board of the National Academies, Washington, D.C., 2009.

Calgary Transit. Bus-Only Crossings website. http://www.calgarytransit.com/html/bus_only_crossings.html, accessed September 30, 2014.

Carry, W., E. Donnell, Z. Rado, M. Hartman, and S. Scalici. Red Bus Lane Treatment Evaluation. Paper 14-4649. Presented at the 93rd Annual Meeting of the Transportation Research Board, Washington, D.C., January 2014.

Cesme, B., S. Altun, and B. Lane. Queue Jump Lane, Transit Signal Priority, and Stop Location: Evaluation of Transit Preferential Treatments Using Microsimulation. Paper 15-0678. Presented at the 94th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2015.

City of Lund. Se upp för bussen på Tornavägen! (Watch out for the bus on Tornavägen!). http://www.lund.se/Tillbehor/Nyhetsarkiv/Busskorfalt-oppnas-pa-Tornavagen/. Lund, Sweden, August 26, 2011, accessed March 10, 2015.

Corby, M., V. Ermatinger, E. Peissel, R. Stewart, and R. Wong. Guidelines for Planning and Implementation of Transit Priority Measures. Transportation Association of Canada, Ottawa, Canada, May 2013.

Corey, J., Y. Lao, and Y. Wang. Quantifying and Comparing Left Turn Strategy Travel Time and Queuing Performance. Paper 13-2868. Presented at the 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., January 2013.

CROW. *Design Manual for Bicycle Traffic.* Ede, The Netherlands, June 2007.

Danaher, A. R. *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic.* Transportation Research Board of the National Academies, Washington, D.C., 2010.

Diaz, R. B. and D. Hinebaugh. Characteristics of Bus Rapid Transit for Decision-Making. Federal Transit Administration, Washington, D.C., February 2009.

Dixon, K. K. et al. NCHRP Project 03-99, "Development and Application of Access Management Guidelines." Final Report, not yet published.

Eccles, K. A., H. S. Levinson, Center for Urban Transportation Research, and Livable Streets, Inc. *TCRP Report 117: Design, Operation, and Safety of At-Grade Crossings of Exclusive Busways.* Transportation Research Board of the National Academies, Washington, D.C., 2007.

El-Geneidy, A. M., J. G. Strathman, T. J. Kimpel, and D. T. Crout. Effects of Bus Stop Consolidation on Passenger Activity and Transit Operations. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1971*, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 32–41.

European Platform on Mobility Management. The EPOMM Modal Split (TEMS) website. http://www.epomm.eu/tems/index.phtml, accessed September 3, 2013.

Feng, W., M. Figliozzi, and R. L. Bertini. Quantifying the Joint Impacts of Stop Locations, Signalized Intersections, and Traffic Conditions on Bus Travel Time. Paper 15-5427. Presented at the 94th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2015.

FHWA. *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition, incorporating Revisions 1 and 2, 2012.

FHWA. Context Sensitive Solutions Primer. http://www.fhwa.dot.gov/planning/csstp/css_primer/docs/FHWA_CSS_Primer.pdf. 2014. Accessed December 4, 2014.

Fitzpatrick, K., K. M. Hall, S. Farnsworth, and M. D. Finley. *TCRP Report 65: Evaluation of Bus Bulbs.* TRB, National Research Council, Washington, D.C., 2001.

Florida DOT. District 4 Transit Facilities Guidelines. Version 3. Fort Lauderdale, Florida, October 2007.

FTA. Title VI Requirements and Guidelines for Federal Transit Administration Recipients. FTA Circular 4702.1B. U.S. Department of Transportation, Washington, D.C., October 1, 2012.

Furth, P. G., B. Hemily, T. H. J. Muller, and J. Strathman. *TCRP Report 113: Using Archived AVL-APC Data to Improve Transit Performance and Management.* Transportation Research Board of the National Academies, Washington, D.C., 2006.

Furth, P. G. and J. L. SanClemente. Near-Side, Far-Side, Uphill, Downhill: Impact of Bus Stop Location on Bus Delay. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1971*, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 66–73.

Gardner, K., C. D'Souza, N. Hounsell, B. Shrestha, and D. Bretherton. Review of Bus Priority at Traffic Signals Around the World. UITP Bus Committee, Brussels, Belgium, April 2009.

Greater Manchester Public Transport Authority. Quality Bus Corridors in Greater Manchester: Best Practice Guidelines. Manchester, U.K., 2007.

Guler, S. I. and M. Menendez. Empirical Evaluation of Bus and Car Delays at Pre-signals. Presented at the 13th Swiss Transport Research Conference, Ascona, Switzerland, April 2013.

Hemily, B. and R. D. King. *TCRP Synthesis 75: Uses of Higher Capacity Buses in Transit Service.* Transportation Research Board of the National Academies, Washington, D.C., 2008.

Hillsman, E. L., S. J. Hendricks, and J. K. Fiebe. A Summary of Design, Policies and Operational Characteristics for Shared Bicycle/Bus Lanes. National Center for Transit Research, University of South Florida, Tampa, July 2012.

Hodge, V. J., T. Jackson, and J. Austin. Optimising Activation of Bus Pre-signals. In Proceedings, International Conference on Models and Technologies for Intelligent Transportation Systems, Rome, Italy, June 2009.

Jordan, C., N. Kajdy, and N. McKendrick. Bus Priority Measures in Calgary: Past, Present and Future. Presented at the 2010 Annual Conference of the Transportation Association of Canada, Halifax, Nova Scotia, September 2010.

Kimpel, T., J. Strathman, R. Bertini, and S. Callas. Analysis of Transit Signal Priority Using Archived TriMet Bus Dispatch System Data. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1925.* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 155–166.

King, R. D. *TCRP Synthesis 49: Yield to Bus—State of the Practice.* Transportation Research Board of the National Academies, Washington, D.C., 2003.

Kittelson & Associates, Inc., Herbert S. Levinson Transportation Consultants, and DMJM+Harris. *TCRP Report 118: Bus Rapid Transit Practitioner's Guide.* Transportation Research Board of the National Academies, Washington, D.C., 2007.

Kittelson & Associates, Inc., Parsons Brinckerhoff, KFH Group, Inc., Texas A&M Transportation Institute, and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition. Transportation Research Board of the National Academies, Washington, D.C., 2013.

Koonce, P., P. Ryus, D. Zagel, Y. Park, and J. Parks. An Evaluation of Comprehensive Transit Improvements—TriMet's Streamline Program. In *Journal of Public Transportation*, Vol. 9., No. 3, 2006, pp. 103–116.

Koumara, S. S. P., N. B. Hounsell, and T. J. Cherrett. Evaluating Bus Priority and Queue Relocation Techniques of Pre-Signals. Paper 07-0495. Presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2007.

Larwin, T. F. and Y. Koprowski. *TCRP Synthesis 96: Off-Board Fare Payment Using Proof-of-Payment Verification.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Lavrenz, S. M., C. M. Day, A. M. Hainen, W. B. Smith, A. L. Stevens, H. Yi, and D. Bullock. Characterizing Signalized Intersection Performance using Maximum Vehicle Delay. Paper 15-0385. Presented at the 94th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2015.

Levinson, H. S., C. L. Adams, and W. F. Hoey. *NCHRP Report 155: Bus Use of Highways—Planning and Design Guidelines.* TRB, National Research Council, Washington, D.C., 1975.

Levinson, H., S. Zimmerman, J. Clinger, S. Rutherford, R. L. Smith, J. Cracknell, and R. Soberman. *TCRP Report 90: Bus Rapid Transit, Volume 1: Case Studies in Bus Rapid Transit.* Transportation Research Board of the National Academies, Washington, D.C., 2003.

Lindley, J. A. MUTCD—Interim Approval for Optional Use of a Bicycle Signal Face (IA-16). Federal Highway Administration, Washington, D.C., December 24, 2013.

Martin, P., H. S. Levinson, and Texas Transportation Institute. *TCRP Report 151: A Guide for Implementing Bus On Shoulder (BOS) Systems.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Mirabdal, J. and B. Thesen. Using Video Detection for Transit Priority. Presented at the 2002 Institute of Transportation Engineers Annual Meeting, Philadelphia, Pa., Aug. 2002.

Multisystems, Inc., Mundle & Associates, Inc., and Simon & Simon Research and Associates, Inc. *TCRP Report 94: Fare Policies, Structures, and Technologies: Update.* Transportation Research Board of the National Academies, Washington, D.C., 2003.

NACTO. *Urban Bikeway Design Guide*, 2nd Edition. New York, 2012.

NACTO. *Urban Street Design Guide.* Island Press, Washington, D.C., 2013.

NCUTCD. Proposed New Section 8E: Busway Grade Crossings. June 28, 2014(a). http://ncutcd.org/doc/Attach%2011%20RRLRT%20No2%20Busways.pdf, accessed February 22, 2015.

NCUTCD. Chapter 3G: Colored Pavements. June 28, 2014(b). http://ncutcd.org/doc/Attach%2016%20Markings%20No1%20Chapter%203G%20Colored%20Pavements.pdf, accessed February 24, 2015.

Nevers, B., H. Steyn, Y. Mereszczak, Z. Clark, N. Rouphail, J. Hummer, B. Schroeder, Z. Bugg, J. Bonneson, and D. Rhodes. *NCHRP Report 707: Guidelines on the Use of Auxiliary Through Lanes at Signalized Intersections.* Transportation Research Board of the National Academies, Washington, D.C., 2011.

New York City DOT. 2012 Bus Lane Camera Enforcement Update Report. New York, 2012.

New York City DOT. Third Avenue Transit Improvements. Presentation to Manhattan Community Board 6 Transportation Committee, May 6, 2014.

New York City DOT and MTA-NYCT. M15 on First and Second Avenues: Progress Report. New York, 2011.

New York City DOT and MTA-NYCT. Select Bus Service: Bx41 on Webster Avenue—Progress Report. New York, August 2014.

Public Transport Authority of Western Australia. A Practitioner's Guide to Bus Movement and Priority: A Framework for Supporting Transit in Western Australia. Perth, March 2011.

Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O'Brien. *NCHRP Report 672: Roundabouts: An Informational Guide*, 2nd Edition. Transportation Research Board of the National Academies, Washington, D.C., 2010.

Ryus, P., K. Laustsen, K. Blume, T. Urbanik, K. Lee, S. Beaird, E. Lindstrom, J. Crisafi, Z. Bugg, A. Skabardonis, and S. Langdon. *TCRP Web-Only Document 66: Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies.* TCRP Project A-39 Final Report. Transportation Research Board of the National Academies, Washington, D.C., 2015.

Safran, J. S., E. B. Beaton, and R. Thompson. Factors Contributing to Bus Lane Obstruction and Usage in New York City: Does Design Matter? Paper 14-2749. Presented at the 93rd Annual Meeting of the Transportation Research Board, Washington, D.C., January 2014.

St. Jacques, K. and H. S. Levinson. *TCRP Report 26: Operational Analysis of Bus Lanes.* TRB, National Research Council, Washington, D.C., 1997.

St. Jacques, K. and H. S. Levinson. *TCRP Research Results Digest 38: Operational Analysis of Bus Lanes on Arterials: Application and Refinement.* TRB, National Research Council, Washington, D.C., 2000.

Seskin, S. and B. McCann. Complete Streets Local Policy Workbook. Smart Growth America, Washington, D.C., Spring 2013.

SFMTA. Guidelines for Accessible Building Blocks for Bicycle Facilities. San Francisco, California, 2014.

SFMTA. Transit Only Lane Enforcement Program Overview. San Francisco, California, May 18, 2012.

Skehan, S. Traffic Signal Priority for Metro Rapid Buses: The Los Angeles Experience. Presented at the 2001 Institute of Transportation Engineers Annual Meeting, Chicago, Ill., 2001.

Smith, Jr., D. T. and D. Appleyard. *State of the Art: Residential Traffic Management.* Report FHWA/RD-80/092. Federal Highway Administration, Washington, D.C., 1980.

Smith, H. R., B. Hemily, and M. Ivanovic. *Transit Signal Priority (TSP): A Planning and Implementation Handbook.* ITS America, Washington, D.C., May 2005.

Suderman, S. and J. Redmond. The Pembina Highway Buffered Bike Lanes Project—A Solution to Managing Cyclists, Buses, and Pedestrians at Transit Stops. Presented at the 2013 Meeting of the Transportation Association of Canada, Winnipeg, Manitoba, Canada, September 2013.

Texas Transportation Institute. *TCRP Report 19: Guidelines for the Location and Design of Bus Stops.* TRB, National Research Council, Washington, D.C., 1996.

Thomas, L. W. *TCRP Legal Research Digest 42: Transit Agency Intergovernmental Agreements: Common Issues and Solutions.* Transportation Research Board of the National Academies, Washington, D.C., November 2012.

TransLink. TransLink Transit Infrastructure Design Guidelines. Vancouver, Canada, January 2002.

Transport for London. Traffic Enforcement: Impact Analysis and Future Strategies. London, U.K., June 2006.

Transportation Research Board of the National Academies. *Highway Capacity Manual 2010.* Washington, D.C., 2010.

TriMet. TriMet Design Criteria. Portland, Oregon, March 2005.

TriMet. Bus Stop Guidelines. Portland, Oregon, July 2010.

U.K. Department for Transport. Bus Priority—The Way Ahead. Resource Pack Edition 2. London, December 2004.

Urbanik, T., A. Tanaka, B. Lozner, E. Lindstrom, K. Lee, S. Quayle, S. Beaird, S. Tsoi, P. Ryus, D. Gettman, S. Sunkari, K. Balke, and D. Bullock. *NCHRP Report 812: Signal Timing Manual*, 2nd Edition. Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine, Washington, D.C., 2015.

U.S. Access Board. ADA Standards for Transportation Facilities. 2006. http://www.access-board.gov/guidelines-and-standards/transportation/facilities/about-the-ada-standards-for-transportation-facilities/ada-standards-for-transportation-facilities-single-file#a810, accessed November 2, 2014.

U.S. Access Board. Proposed Guidelines for Pedestrian Facilities in the Public Right-of-Way. July 26, 2011. http://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/proposed-rights-of-way-guidelines, accessed November 2, 2014.

U.S. Access Board. Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way; Shared Use Paths—5. Conflicts Between Shared Path Users. 2013. http://www.access-board.gov/guidelines-and-standards/streets-sidewalks/shared-use-paths/supplemental-notice/conflicts-between-shared-path-users, accessed November 2, 2014.

Walker, J. *Human Transit.* Island Press, Washington, D.C., 2012.

Wedeby, B., T. Olsson, and P. Wisenborn. Tillsammans skapar vi "Sveriges bästa busslinje"—Hur blev det då? (Together we create "Sweden's best bus line"—How did it happen?). Presented at Trafik- och gatudagar 2014, Swedish Association of Local Authorities and Regions, Stockholm, Oct. 2014. http://skl.se/download/18.2064a667148a7e3a2b68b18a/1413467952886/Per+Wisenborn_MEX+141014+SKL+v2.pdf, accessed March 10, 2015.

Williams, K., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual*, 2nd Edition. Transportation Research Board of the National Academies, Washington, D.C., 2014.

Zhou, H., S. Bromfield, and P. Lin. An Overview of Yield-to-Bus Programs in Florida. In *Journal of Public Transportation*, Vol. 14, No. 2, 2011, pp. 151–163.

Photo and Illustration Credits

Kelly Blume: Section 5.2, Figure C-1 (b, d)
Federal Highway Administration/Parsons Brinckerhoff "HOV Interactive 1.0": Table 4 (#6), Section 8.6
Kevin Lee: Section 6.4
Malmö Streets and Parks Department: Section 5.5
Patrick McMahon: Section 6.12
Minnesota DOT: Table 3 (#4), Section 7.3
New York City DOT: Table 4 (#4), Section 8.4, Figure C-1 (e)
Victoria Perk: Section 8.7
Lee Rodegerdts: Section 6.1
John Ryus: Table 3 (#5), Table 4 (#5), Section 8.5
Paul Ryus: Table 1 (#5), Table 2 (#3, 9, 10, 11, 12), Table 3 (#1, 2, 3, 6, 8), Table 4 (#1, 2, 3, 7, 8, 9), Sections 5.1, 5.4, 6.3, 6.9, 6.10, 6.11, 6.13, 7.1, 7.2, 7.5, 7.7, 8.1, 8.2, 8.3, 8.8, and 8.9, Figure C-1 (a, f)
Yolanda Takesian: Figure C-1 (c)
NCHRP Report 812: Signal Timing Manual, 2nd Edition (Urbanik et al. 2015): Table 2 (#5, 7), Sections 6.5 and 6.7
TriMet: Table 1 (#4)
Oran Viriyincy: Section 7.4

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
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	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
FAST	Fixing America's Surface Transportation Act (2015)
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
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
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
TDC	Transit Development Corporation
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

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001

ADDRESS SERVICE REQUESTED

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

The nation turns to the National Academies of Sciences, Engineering, and Medicine for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

ISBN 978-0-309-37509-2
90000
9 780309 375092