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Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies

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Contractor's Final Report for TCRP Project A-39
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Abstract

This report documents the research conducted by TCRP Project A-39, *Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies.* This project conducted an extensive review of transit preferential treatments used in the U.S. and internationally, including information on when these treatments are applied and how they are designed. The project interviewed a number of transit and roadway agencies to identify lessons-learned and best 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. This report also 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, this report presents recommendations for 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.

Summary

INTRODUCTION

Improving bus travel times and travel time reliability are key considerations for transit agencies, as these issues directly impact the cost of providing service and good performance in these areas is important for attracting new ridership. They are also important considerations for planning agencies, as 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; improved transit service can greatly increase the number of people served by a roadway without requiring the need for expensive widening.

However, most transit and roadway agencies still have neither formal programs for developing transit-supportive roadway strategies nor formal intergovernmental agreements with respect to the planning, design, construction, operations, maintenance, and performance monitoring of these strategies. Furthermore, information on this topic, until recently, has mainly been limited to studies of individual projects that frequently implemented multiple changes at the same time, and guidance originally developed in the mid-1970s at a time when the automobile mode was typically prioritized over the transit mode.

This report documents the research conducted by TCRP Project A-39, *Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies* to identify roadway-based strategies for improving transit operations, to develop decision-making guidance on the use of such strategies, to document best practice for developing interagency partnerships to implement these strategies, and to recommend potential changes to other reference documents to facilitate the implementation of these strategies. A companion report developed by this project, *A Guidebook on Transit-Supportive Roadway Strategies,* presents the information developed by this project in a practitioner-friendly format.

Chapters 1 and 2 of this report provide background information and a synthesis of the state of the practice related to transit-supportive roadway strategies. Chapters 3 and 4 focus on the project's fact-finding and original research elements. Chapter 5 presents the research conclusions and suggestions for additional future research.

STATE OF THE PRACTICE

Types of Strategies

There are many different types of transit-supportive roadway strategies in common use in the United States and many different ways have been proposed to categorize them. The *Transit Capacity and Quality of Service Manual* (Kittelson & Associates et al. 2013) describes infrastructure strategies (primarily under the control of a roadway agency) and operational strategies (primarily under the control of a transit agency). AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets* (2014) uses bus stop, roadway lanes, intelligent transportation systems (ITS), and enforcement as strategy categories. Canadian guidelines (Corby et al. 2013) divide strategies into regulatory, transit signal priority (TSP), and physical measure categories.

Adding to the challenge of categorizing strategies is that some common types of treatments are composed of a variety of elements. For example, a *queue jump* may include (1) a short section of bus lane or a bus exemption from the requirement to turn right from a right-turn lane, (2) a phase inserted into the traffic signal cycle that gives buses a head start over parallel traffic, (3) special transit signal faces displaying vertical and horizontal bars to control bus movements, and (4) signing and pavement marking to supplement the above elements. A bus lane could be considered both an infrastructure strategy (involving an extended stretch of roadway) and a regulatory strategy (restricting the use of the lane by non-transit vehicles).

For the purposes of this report*,* the following categories of strategies are defined:

- **Signal timing.** Strategies that primarily alter the normal traffic signal timing to favor a particular bus movement.
- **Regulatory.** Strategies that primarily exempt buses from certain traffic regulations or that restrict other traffic movements.
- **Infrastructure.** Strategies that primarily involve constructing physical improvements or designating portions of the roadway for exclusive (e.g., buses only) or semi-exclusive (e.g., right-turns allowed) bus use.
- **Operations.** Strategies primarily under the control of a transit agency that can help improve bus speeds, travel time reliability, or both. Previous research (e.g., Boyle 2013) has shown that operations strategies can potentially provide significant bus speed and reliability benefits at relatively low cost.
- **Support.** Strategies that generate the fullest possible benefit from other strategies.

Literature Review Findings

Existing Design Guidance

Standards and guidance for the design (e.g., lane widths, traffic control) of transit-supportive roadway strategies are relatively well-established, with information available in the AASHTO Transit Guide (AAHSTO 2014), MUTCD (FHWA 2009), various NCHRP and TCRP reports, and some transit agency design guidelines. Therefore, this project did not focus on developing new guidance, except in cases where no or minimal U.S. guidance existed.

Criteria for Implementing Transit-Supportive Strategies

Warrants specifying minimum bus volumes required to implement particular strategies have been provided in various NCHRP and TCRP reports; all of these warrants can be traced back to *NCHRP Report 155* (Levinson et al. 1975). More recent guidance, including the AASHTO transit design guide (2014), Canadian guidelines (Corby et al. 2013), and the TCQSM (Kittelson & Associates et al. 2013)—as well as the evolution of transportation engineering practice toward context-sensitive solutions and complete streets—suggests that a broader range of factors should be considered when evaluating potential strategies. In addition, this project's interviews and literature review found that many projects have been implemented with bus volumes well below the *NCHRP Report 155* warrants, particularly when implemented in conjunction with BRT projects. Therefore, this project's recommendations avoid the use of warrants in favor of evaluating the project within the context of the local policy environment, while still providing ranges of bus volumes in which a particular strategy may be most appropriate. The outcome of this approach is that environments that prioritize automobile operations will require higher bus volumes to implement a strategy than ones that prioritize transit operations. This approach also promotes the consideration of multiple factors and not just bus volumes.

Agency Interview Findings

Interviews were held with transit and roadway agency staff in U.S. and Canadian cities at two points during the project, focusing on (1) identifying processes used to develop interagency partnerships and (2) documenting unpublished benefits of transit preferential strategies. Three other interviews were conducted in response to panel member requests; two to obtain the perspectives of bicyclists, and one with Sweden's third-largest city, Malmö, as the city has a well-established process for interagency cooperation for implementing transit projects. Regions were selected on the basis of (1) having implemented transit-supportive roadway treatments, (2) geographic variety, and (3) to the extent possible, region size variety.

Key findings of these interviews include:

- Regular communication between transit and roadway agencies is essential, to help staff understand each other's needs, to develop relationships and trust from working together, and to work together to address joint transportation issues. Regular communication can have pay-offs beyond a single project, such as in day-to-day transit operations (e.g., planning for construction detours).
- Many initial projects arose from taking advantage of opportunities that came up—for example, roadway projects that could incorporate transit features or could take advantage of grant funding obtained by the transit agency. In these cases, having a project already identified and in a local or regional transportation plan helped. Other projects took advantage of "low-hanging fruit," where it was not particularly difficult to implement transit-supportive treatments, a project benefitted a large number of transit passengers, or both. Transit operational improvements were usually implemented in conjunction with physical improvements and the operational improvements often provided the majority of the transit benefit.

Nevertheless, including the physical improvements as part of the overall project allowed agency staff and roadway users to gain experience with them and build support for future implementations.

- Performing a traffic analysis of the effects of a proposed strategy in the specific context where it would be implemented helps engage traffic engineering staff (i.e., quantifying roadway performance for a specific location or corridor will be received better than qualitative reports of how a treatment has performed elsewhere). One transit agency interviewee commented that "working with engineers isn't hard—just give them data and talk objectively, they want a smart solution."
- Stakeholders should be involved early and an overall plan for stakeholder engagement developed to successfully implement transit-supportive strategies.
- Several interviewees from both transit and roadway agencies acknowledged that not all roadway agency staff are open to transit-supportive strategies. In roadway agencies with progressive leadership, this was addressed by "siloing" those staff to work on projects where they didn't have to deal with transit. In other cases, the roadway agency culture gradually evolved. Transit agencies found success in working with individual agency staff or (in multi-jurisdictional environments) jurisdictions who were open to transit improvements.
- Depending on the local driving culture, enforcement can be an important ingredient for successfully implementing some types of transit-supportive treatments. Close coordination with the appropriate law enforcement agency (as early as the initial planning stage, as law enforcement may not be willing to enforce something they haven't been consulted on) is essential when enforcement will be required for a successful outcome.

Knowledge Gaps

The following are key knowledge gaps relating to transit-supportive roadway strategies that were identified through the review of the state of the practice:

- How bus stop location, dwell time, dwell time variability, and traffic signal location and timing influence the effectiveness of various strategies. In particular, determining whether or not the effect of a treatment will be lost at the next traffic signal.
- More-specific information on the travel time and travel time reliability benefits of various strategies, eliminating the confounding effects of other actions (e.g., signal retiming, stop consolidation).
- Developing guidance on using (or not using) innovative treatments that were not addressed in the documents included in the U.S. portion of the literature review:
    - Pre-signals: signals placed in advance of a signalized intersection to manage traffic on the intersection approach
    - Bi-directional bus lane operation

- Special bus signal phases to allow unusual turning movements
- Center bus lanes to the right of left-turn lanes
- Double-cycling phases used by transit
- Bus-only links
- "Shadowing" treatments: using upstream traffic signals or pedestrian beacons to create gaps in traffic so that buses can make turning movements with less delay

RESEARCH APPROACH

The following research tasks were conducted to address the gaps in knowledge:

- Developing an analytical approach for estimating the impacts of transit signal priority at signalized intersections, using the analysis procedures given in the *Highway Capacity Manual 2010* and for predicting when the benefit of a strategy implemented at one intersection might be lost at a downstream intersection (e.g., a bus departs an upstream traffic signal early, only to wait longer at the next signal).
- Investigating how different local policy environments might impact a transit agency's approach to implementing transit-supportive roadway strategies, and investigating the feasibility of a spreadsheet tool to estimate the impact of strategies under different traffic control, traffic demand, and roadway geometry scenarios.
- Seeking automatic vehicle location data from transit agencies that (1) archive such data and (2) have implemented individual strategies (as opposed to packages of strategies).
- Conducting a simulation study to identify the benefits of selected strategies in a controlled setting.
- Reviewing international best practice on "innovative" strategies not in common use in the U.S. and assessing the strategies' potential for application in the U.S.
- Identifying potential modifications to the MUTCD required to support the implementation of promising strategies.
- Reviewing AASHTO's transit design guide (2014) and making recommendations for changes and additions in a future edition, based on the findings of this project.

All of these tasks contributed information used in the development of this project's main product, *A Guidebook on Transit-Supportive Roadway Strategies.*

FINDINGS

Benefits of Transit-Supportive Roadway Strategies

The literature indicates that operational improvements (e.g., increased stop spacing, off-board fare payment) often provide the majority of the travel time or speed benefit when multiple strategies are implemented at the same time. *TCRP Synthesis 110* (Boyle 2013) noted that “successful agencies emphasized good ideas above technology. TSP and other traffic engineering actions topped the ‘wish list’ of responding agencies, but most of the successful actions could be implemented without new or added technology” (or infrastructure).

This project found similar results, in that bus operations strategies were often found to produce similar or better benefits for buses than strategies focused on infrastructure or technology. The project’s simulation study found that relocating a bus stop from the near side to a far side produced similar delay savings for buses as implementing TSP. The combination of TSP and stop relocation to the far side produced bus delay savings that were approximately additive (i.e., the benefit of the two strategies combined was approximately the same as the sum of the benefits from the two strategies if implemented individually). An analysis of AVL data from a 5-mile portion of a BRT line in Seattle, where different strategies were implemented separately (business access and transit lanes, traffic-responsive signal timing, and off-board fare payment and headway changes) found that only the operational changes resulted in shorter bus travel times through the corridor.

This project also confirmed through simulation that the benefits of TSP and other strategies applied at spot locations, while appearing to be beneficial on an individual intersection basis, may in some cases not produce significant bus time savings when evaluated on a corridor basis. One potential cause for this result is that the next downstream signal can negate the delay benefit from an upstream signal. 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. This project developed an analytical method for estimating the likelihood that a bus will be able to make the green light at a downstream signal, thus preserving the delay benefit provided by a strategy implemented upstream, building on work by St. Jacques and Levinson (1997).

This is not to say that signal timing, regulatory, and infrastructure strategies have no role to play. On the contrary, many strategies of these types were found that provide meaningful transit benefits. Operational strategies are well-suited to combining with other strategies to produce a greater benefit than could be achieved by either in isolation. In addition, operational strategies provide a low-cost, readily implementable starting point for improving bus speeds and reliability in jurisdictions where transit service is not prioritized.

Innovative Strategies

This project reviewed international best practice for strategies that were identified through the literature review or agency interviews as (1) being regularly used internationally but not in the U.S., lacking U.S. guidance on their use, or both. Implementation guidance was developed for the following strategies:

- *Bus-only signal phases* that allow buses to make unconventional turning movements at intersections (e.g., left turns from the right lane).

- *Pre-signals* that can be used to (1) create a virtual bus lane on an intersection approach where a physical bus lane is infeasible, (2) to help buses weave across traffic lanes from a bus lane to enter a left-turn lane, and (3) to help buses merge into traffic at the point a bus lane ends.
- *Bus-only links* that provide connections between subdivisions, or allow bus access to activity center areas where general traffic is undesired.
- *Bus boarding islands,* which allow bus stops to be located within the roadway and help support strategies such as queue jumps at intersections with channelized right-turn lanes and left-side bus lanes.
- *Reversible bus lanes,* that switch direction by time of day or on an as-needed basis as buses arrive.
- *Phase reservice,* in which a minor movement (e.g., a protected left turn or a minor street approach) is served twice within the same cycle, which can reduce delay for buses making those movements.
- Techniques for assisting buses with making left turns onto or off of busy streets, including "shadowing" treatments that create a gap in traffic using a nearby traffic signal and discussing opportunities for installing a traffic signal.

Guidance was also developed for managing bus and bicycle interactions at and between bus stops, on the basis of U.S. and international best practice. This guidance appears in the companion Guidebook as Appendix C.

Chapter 1. Background

OVERVIEW

This report documents the research conducted by TCRP Project A-39, *Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies.* A companion document developed by this project, A *Guidebook on Transit-Supportive Roadway Strategies,* provides recommendations on selecting strategies to address a particular bus speed or reliability problem and guidance on achieving a successful implementation.

This chapter presents the research problem statement that led to this project, summarizes the work tasks involved in conducting the research, describes the report's organization, and provides a few comments on the nomenclature used by this report.

RESEARCH PROBLEM STATEMENT

Background

With transportation demand outpacing capacity expansion in many regions, transportation networks and roadways are facing increasing congestion. The provision of transit-supportive strategies to reduce travel time, improve reliability, and provide operational cost savings is becoming increasingly important. Transportation management measures that obtain more capacity out of existing resources must be explored in order to provide financially viable transportation solutions. Transit-supportive strategies include both intersection treatments such as transit signal priority, special signal phasing, queue jump lanes and signals, bypass lanes and curb extensions, and roadway segment treatments such as exclusive or shared transit lanes within the travelled way, exclusive transitways (typically in the median), and corridor signal progressions favoring transit operations. Partnering of transit and highway/traffic agencies throughout the project development process is necessary but not sufficient; a clear understanding of the criteria for and costs and impacts of such strategies are critical to the implementation of transit-supportive strategies.

TCRP Synthesis 83: Bus and Rail Preferential Treatments in Mixed Traffic began the process of obtaining information on the type and extent of recent urban street transit-priority treatment implementation in North America, including some representative examples of successful transit and highway/traffic agency partnering strategies, and identified key areas for future research. It provided a partial updating of *NCHRP Report 155: Bus Use of Highways: Planning and Design Guidelines.*

Most transit and highway/traffic agencies still have neither formal transit preferential treatment programs nor formal intergovernmental agreements with respect to planning, design, construction, operations/maintenance, and performance monitoring of treatments. Research is needed to (a) identify processes for establishing transit preferential treatment needs on a spot improvement, corridor, and regional scale, and (b) identify implementation strategies.

Objectives

The objectives of this research were to (1) identify consistent and uniform strategies to improve transportation network efficiency to reduce delay and improve reliability for transit operations on roadways; (2) develop 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) identify the components of model institutional structures and/or intergovernmental agreements for successful implementation; and (4) identify potential changes to the *Manual on Uniform Traffic Control Devices* (MUTCD) and related documents to facilitate implementation of selected strategies.

RESEARCH TASKS

The research effort was divided into the following tasks:

- **Task 1, Guidance Oriented Toward Transit Agencies** and **Task 2, Guidance Oriented Toward Highway/Traffic Agencies,** which included a literature review on how the respective agency types make decisions to implement (a) signals, signs, and markings and (b) geometric designs supportive of transit operations on streets and highways. The review also identified, to the extent available, (a) capital costs; (b) the effects on bicycle and pedestrian access (including those with disabilities); (c) safety; (d) on-time performance; (e) travel time savings and their perception; (f) ridership; (g) transit operational cost savings; (h) public acceptance; (i) enforcement; (j) capacity/congestion; (k) person and vehicle delay; (l) maintenance; (m) operating costs; (n) constructability; and (o) legal precedents associated with specific types of transit-supportive treatments. Finally, a selection of transit and roadway agencies were interviewed to identify specific strategies they had implemented and how they had formed partnerships with each other and other stakeholders to successfully plan and implement these strategies.
- **Task 3, Interim Report,** documenting the results of Tasks 1 and 2 and proposing a work plan for the remainder of the project.
- **Task 4, Collect and Analyze Data,** which included the following subtasks:
    - **Task 4A, Transit Signal Priority (TSP) Theory Advancement,** which sought to develop an easy-to-use method for identifying the feasibility and "usefulness" of TSP at a given signalized intersection, considering both the impacts of TSP at the subject intersection and the progression at the next downstream intersection;
    - **Task 4B, Policy Threshold Development,** which expanded on the literature review to explore the different local policy contexts in which transit preferential strategies have been implemented, and the implications for

developing warrants or recommended conditions for implementing strategies;

    - **Task 4C, Treatment Evaluation Using Automatic Vehicle Location (AVL) Data,** which sought out projects where specific strategies had been implemented in isolation or in series, and where AVL data was available to allow a before-and-after evaluation of the effect of the project on bus operations; and
    - **Task 4D, Simulation Study,** which modeled a real-world arterial street and tested the impact of different types of strategies on bus operations, under varying traffic conditions.
- **Task 5, Standards and Guidance Modifications,** which included the following subtasks:
    - **Task 5A, Manual on Uniform Traffic Control Devices (MUTCD),** which reviewed the need for (a) revising the MUTCD to allow certain types of innovative strategies and (b) developing model experimentation requests for promising strategies;
    - **Task 5B, AASHTO Guide for Design of Transit Facilities on Highways and Streets,** which reviewed the final version of this guide, which was published toward the end of this research effort, (a) to identify guidance that should be incorporated in this project's guidebook and (b) to recommend potential changes for a future edition reflective of the findings of this project; and
    - **Task 5C, Innovative Strategies,** which identified international best practice for promising transit preferential strategies that have had few or no implementations to date in the United States.
- **Task 6, Implementation Guidance,** which included the following subtasks:
    - **Task 6A, Follow-up Activities,** which included additional agency interviews focusing on partnership efforts, and reviews of new literature that had been published since the start of the project;
    - **Task 6B, Guidebook,** which developed the *Guidebook on the Implementation of Transit Preferential Roadway Strategies*; and
    - **Task 6C, Final Report,** which developed this report documenting the project's activities and an accompanying PowerPoint presentation on the project.

REPORT ORGANIZATION

Chapter 2 of this report provides a brief overview of the types of transit-supportive treatments in common use in the United States at the time of writing, and summarizes the findings from the literature review and interviews (Tasks 1, 2, and 6A). Chapter 3 describes the process used by each of Task 4 and 5 subtasks to gather information relevant to the research effort. Chapter 4 summarizes the project's key findings and how they can potentially be used. Chapter 5 provides the research effort's conclusions and suggestions for future research. Chapter 6 provides a complete list of references used in this report. Finally, a series of appendices provides details about each subtask's activities and results.

NOMENCLATURE

This research effort primarily focused on the operational effects of transit-supportive roadway strategies (also known as *transit preferential treatments*) on the bus mode operating on surface streets. In many cases, these treatments can also be applied to other transit modes that operate on surface streets, such as demand-response transit, streetcar, and light rail. However, unless stated specifically otherwise, all findings are specific to the bus mode.

The accompanying *Guidebook on the Implementation of Transit Preferential Roadway Strategies* (shortened to *Guidebook* in the remainder of this report) provides a glossary of traffic engineering and transit terms used both in the guidebook and this final report. Transit terminology is not standardized and the names of strategies used in this report (e.g., curb extensions) may not match local terminology (e.g., bus bulbs). An effort has been made to list alternative names for a particular strategy the first time it is used in a chapter.

The names of two other frequently referenced documents are also shortened for convenience: AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014) is referred to as the "AASHTO Transit Guide" throughout this report, while *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd Edition (Kittelson & Associates et al. 2013) is referred to as the TCQSM.

Chapter 2. State of the Practice

INTRODUCTION

This chapter presents the state of the practice in the United States for transit preferential roadway strategies, as identified by TCRP Project A-39. It begins with a brief overview of the types of strategies in common use in the United States. The chapter then summarizes the information about these strategies that was obtained from the project's literature review, initial agency interviews, and follow-up agency interviews. Finally, the chapter describes techniques that transit agencies have successfully used to partner with roadway agencies to implement these types of strategies.

OVERVIEW OF TRANSIT PREFERENTIAL STRATEGIES USED IN THE UNITED STATES

This section categorizes and defines transit preferential roadway strategies in common use in the United States, to provide a basis for discussing current knowledge about these strategies later in the chapter.

There are many different types of transit preferential strategies in common use in the United States and many different ways have been proposed to categorize them. The TCQSM describes infrastructure strategies (primarily under the control of a roadway agency) and operational strategies (primarily under the control of a transit agency). The AASHTO Transit Guide uses bus stop, roadway lanes, intelligent transportation systems (ITS), and enforcement to categorize strategies. Canadian guidelines (Corby et al. 2013) divide strategies into regulatory, transit signal priority (TSP), and physical measure categories.

Adding to the challenge of categorizing strategies is that some common types of treatments are composed of a variety of elements. For example, a *queue jump* may include (1) a short section of bus lane or a bus exemption from the requirement to turn right from a right-turn lane, (2) a phase inserted into the traffic signal cycle that gives buses a head start over parallel traffic, (3) a special transit signal head displaying vertical and horizontal bars to control bus movements, and (4) signing and pavement marking to supplement the above elements. A bus lane could be considered both an infrastructure strategy (involving an extended stretch of roadway) and a regulatory strategy (restricting the use of the lane by non-transit vehicles).

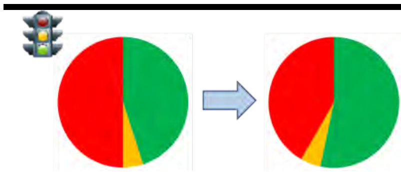
For the purposes of this report, the following categories of strategies are defined:

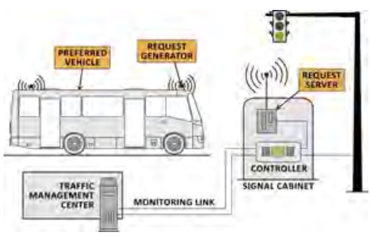
- **Signal timing.** Strategies that primarily alter the normal traffic signal timing to favor a particular bus movement.
- **Regulatory.** Strategies that primarily exempt buses from certain traffic regulations or that restrict other traffic movements.
- **Infrastructure.** Strategies that primarily involve constructing physical improvements or designating portions of the roadway for exclusive (e.g., buses only) or semi-exclusive (e.g., right-turns allowed) bus use.

- **Operations.** Strategies primarily under the control of a transit agency that can help improve bus speeds, travel time reliability, or both.
- **Support.** Strategies that generate the fullest possible benefit from other strategies.

Table 1 through Table 5 briefly describe the types of strategies in common use in the United States that are included in the traffic signal timing, regulatory, infrastructure, operations, and support categories, respectively. Other strategies that have received more use to date internationally than in the U.S. are presented in the "Innovative Strategies" section of Chapter 4 and in Appendix E. The lists below are derived from compilations of strategies provided in the AASHTO Transit Guide, TCQSM, and *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic* (Danaher 2010).

Table 1. Transit Preferential Traffic Signal Timing Strategies





Passive TSP. The traffic signal timing is set to favor transit movement in some way and the timing is provided whether or not a transit vehicle is actually present at a given time. Examples include favoring the street with bus service by allocating more green time to it in the signal plan, reducing potential bus delays by shortening the traffic signal cycle length, and coordinating the signal timing between intersections to progress transit vehicles instead of general traffic.
Green Extension/Red Truncation. The signal timing for an intersection approach is adjusted in response to a request from a transit vehicle to either extend the green time long enough for the vehicle to clear the intersection (*green extension*) or to return to green sooner than normal (*red truncation* or *early return to green*).
Phase Insertion. A phase serving a transit movement is inserted into the traffic signal cycle in response to a request from a transit vehicle, allowing transit vehicles, but not necessarily other vehicles, to move.
Phase Rotation. A phase serving a transit movement (e.g., a left turn arrow or *protected left turn*) is served out of sequence in response to a request from a transit vehicle, thus reducing the delay experienced by that movement.
Pre-emption. Normal traffic signal operation is suspended in order to provide a green indication as soon as possible in response to a request from a transit vehicle. Because of the disruptive effect it causes to signal operations and pedestrian crossing activity, its use today in the U.S. is generally limited to serving emergency vehicles and clearing railroad grade crossings in advance of the arrival of a train, with bus transit being provided with one of the forms of transit signal *priority* described above (Urbanik et al. 2015).

Table 2. Transit Preferential Regulatory Strategies

Turn restrictions. Turning movements (e.g., left turns where no left-turn lane is provided) that create significant delay for other traffic, including transit vehicles, are prohibited during peak periods or at all times.

Movement exemptions. Transit vehicles are allowed to make movements that general traffic is not allowed to make (e.g., proceeding straight from a right-turn lane or making a left turn that is prohibited for other vehicles), thus allowing them to travel along a faster route than they otherwise could.

Parking and delivery restrictions. Parking, deliveries, or both are prohibited during peak periods or at all times. Potential applications include converting the parking lane to a bus lane during peak periods, or removing the traffic friction and delay caused by other vehicles that are trying to maneuver into a parking space, have stopped to pick up or drop off passengers, or have stopped to make deliveries.

Yield-to-bus laws. Vehicles are required to yield to buses that are signaling that they are departing a bus stop, thus reducing the bus delay associated with waiting for a gap in traffic to leave the bus stop.

Table 3. Transit Preferential Infrastructure Strategies

	**Bus lane.** One or more roadway lanes reserved for the exclusive or partial use by buses. They can be located along the curb (*curb bus lane*), in a lane to the left of the curb lane (*interior bus lane*), in the leftmost travel lane (*left-side bus lane*), or in the street median (*median bus lane*). Buses can travel in the same direction as general traffic, against traffic (*contraflow bus lane*), or in either direction at different times (*bi-directional bus lane*). Lanes can operate full-time or part-time, and may allow limited use by other vehicle types (e.g., right-turning vehicles, taxis, bicycles).
	**Shoulder use.** Buses are allowed to use the shoulder during certain times of the day or when certain conditions occur (e.g., vehicles in the general traffic lanes are traveling below a prescribed speed), thus gaining a travel speed advantage over other traffic. *Photo source: Minnesota Department of Transportation.*
	**Queue jump/queue bypass.** Buses are provided with a short bus lane in advance of a traffic signal, or are exempted from the requirement to turn right from a right-turn lane. A bus signal gives buses a head start before parallel traffic receives a green signal, moving them to the front of the queue (if they don't serve a bus stop at the intersection) or allowing them to proceed without having waiting to for a gap in traffic (if they did serve a bus stop at the intersection).
	**Curb extension (*bus bulb*).** The curb is extended out to the edge of the travel lane at a bus stop. Buses can then stop in the travel lane to board and alight passengers, and proceed afterwards along their route without having to wait for a gap to merge back into traffic.

Table 4. Operational Strategies

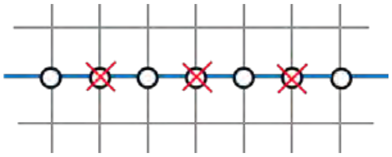
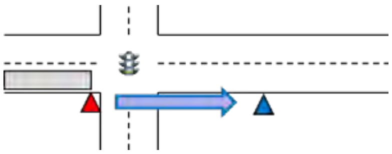
	**Optimize bus stop spacing.** Bus stops are consolidated, moved to other intersections, or both, to improve overall bus speeds. Passengers may need to walk a little farther to access service, but benefit from faster trips, particularly when making longer trips.
	**Bus stop relocation.** The bus stop location is shifted from one side of the intersection to another to improve overall bus speeds. For example, stops can be shifted from near-side to far-side to allow buses to take advantage of the street's traffic signal progression, or stops can be shifted from near-side to far-side to take advantage of an opportunity to construct a curb extension or queue jump.
	**Fare payment changes.** Passengers with pre-paid fares (e.g., bus passes, mobile phone tickets, tickets purchased from a fare machine on the platform) are allowed to use any door to board, thus speeding up the boarding process and reducing dwell time.
	**Bus stop capacity improvements.** The length of the bus stop is increased to allow more buses to serve passengers at the same time and reduce the potential for buses to wait in the street for space to become available to pull up to the stop.
	**Platform improvements.** Platforms at stops used by multiple bus routes can be enlarged to provide more space for waiting passengers, allowing alighting passengers to exit faster and boarding passengers to get to their bus more quickly. Electronic bus arrival information displays help passengers anticipate when, and potentially where, their bus will stop.

Table 5. Support Strategies

	**Enforcement.** Traffic laws relating to transit infrastructure (e.g., bus lane use, parking and stopping restrictions) are regularly enforced to minimize infractions and maximize transit benefits.
	**Signage.** Transit-only use of bus lanes and other infrastructure is clearly signed, to minimize both intentional and unintentional infractions.
	**Pavement markings.** Transit-only use of bus lanes and other infrastructure is clearly marked, to minimize both intentional and unintentional infractions.

LITERATURE REVIEW SUMMARY

Overview

This section summarizes the findings of the literature review conducted for TCRP Project A-39. Appendix A provides the full review. This review focused on relevant domestic and international literature on strategies for planning, designing, and implementing transit preferential strategies. Because a similar review had been conducted for *TCRP Synthesis 83* (Danaher 2010), involving 23 documents, a survey of transit and roadway agencies, and detailed examples of TSP use in four U.S. cities, the TCRP A-39 review focused on identifying documents that had been published after the *TCRP Synthesis 83* review and international documents not included as part of that review, plus a targeted re-review of key references that discuss transit preferential strategies.

The project's literature review included the following components:

- An initial review of 38 reports and papers not included in the *TCRP Synthesis 83* review, 16 state department of transportation (DOT) design manuals, and a number of transit agency design guides. These focused primarily on identifying (1) planning and design guidelines for implementing particular strategies, (2) results of implementing strategies, and (3) descriptions of inter-agency partnerships. The project's interim report presents the results of the initial review in more detail.

- Review of additional documents that were published during the course of the project, including the final version of the AASHTO Transit Guide, Canadian guidelines on transit preferential strategies (Corby et al. 2013), and *TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds* (Boyle 2014).
- Review of 10 additional documents related specifically to addressing bus and bicycle conflicts at and between bus stops.
- Review of 18 additional, primarily international, documents related specifically to "innovative" strategies identified during the initial literature review that have received little or no application to date in the United States.

Comprehensive Overviews of Transit-Supportive Roadway Strategies

The following recent reports and documents describe a broad range of transit preferential strategies in use in the United States and internationally:

- *TCRP Synthesis 83: Bus and Rail and Transit Preferential Treatments in Mixed Traffic* (Danaher 2010);
- *TCRP Report 165: Transit Capacity and Quality of Service Manual, 3rd Edition* (Kittelson & Associates, et al. 2013);
- *Guidelines for Planning and Implementation of Transit Priority Measures* (Corby et al. 2013); and
- *Guide for Geometric Design of Transit Facilities on Highways and Streets* (AASHTO 2014).

Earlier documents, including previous editions of the TCQSM (Kittelson & Associates, et al. 1999 and 2003), the *Highway Capacity Manual* (2000), *TCRP Report 118: Bus Rapid Transit Practitioner's Guide* (Kittelson & Associates, 2007), and *TCRP Report 90: Bus Rapid Transit* (Levinson et al. 2003) have provided quantitative warrants for when selected transit preferential treatments should be considered. All of these can be traced back to *NCHRP Report 155* (Levinson, Adams, and Hoey 1975) as the original source. Although the source material 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 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 each of the general traffic lanes; however, at least in some cases, the recommended minimum bus volumes result in considerably higher person volumes in the bus lane relative to a typical urban street general traffic lane.

The TCRP Project A-39 literature review and agency interviews indicate that many strategies have been implemented with much lower bus volumes than suggested by the *NCHRP Report 155* warrants. The most recent guidance documents suggest considering a broad range of factors when considering transit preferential strategies, consistent with the evolution of traffic engineering practice toward context-sensitive solutions (e.g., FHWA 2014). This suggests that the local *policy environment* must be considered when evaluating transit preferential strategies, as local policies favoring alternative modes could justify strategies at lower bus or passenger volumes than would be justified based solely on roadway operational performance measures such as delay or throughput.

State DOT Roadway Design Manuals

The roadway design manuals from 16 state DOTs were reviewed, along with applicable companion documents (e.g., pedestrian and bicycle design guidelines, signal timing manuals, state MUTCD supplement) that existed in a given state. The DOTs were selected on the basis of operating transit service (Connecticut, Maryland, New Jersey), size (California, Florida, Illinois, New York, Texas), known involvement in transit projects on state highways (Minnesota, Oregon, Utah, Washington), and geographic balance (Arizona, Colorado, Massachusetts, North Carolina).

In most cases, transit was not addressed at all within the design manuals, or only addressed to the extent of providing design guidance for bus pullouts (most common), bus stops, and park-and-ride lots. Only two states—Oregon and Washington—had a chapter on transit facilities within their manuals. A larger number of states had a chapter on pedestrian and bicycle facilities, and curb extensions were sometimes discussed in the context of a being a pedestrian treatment.

The review of state DOT guidance suggests that transit preferential strategies are rarely addressed in DOT design standards. As a result, transit agencies wishing to install apply them on state highways will likely face both an educational effort to inform DOT decision-makers about the benefits and effects of such strategies, and a need for the DOT to develop their own guidance or standards for implementing and designing them. Both of these efforts will likely take time the first time a particular treatment is proposed.

Transit Agency Design Guides

A number of transit agency design guides were reviewed to identify potential guidance on transit preferential strategies; however, most did not provide any such guidance. Five that did were the following:

- TriMet (Portland, Oregon);
- TransLink (Vancouver, Canada);
- Movia (Copenhagen, Denmark);
- Auckland Regional Transport Authority (New Zealand); and
- Public Transport of Authority of Western Australia (Perth).

Given the number of comprehensive documents on transit preferential strategies now available (including this project's Guidebook), it may no longer be necessary for transit agencies to develop their own documents specific to transit preferential strategies, as they can now refer to one or more comprehensive documents of their choosing. However, it could be still be useful for transit agencies to identify preferred (or not preferred) transit preferential strategies, dimensions, and conditions for installation, specific to their own bus fleet and local conditions, as part of their overall design guidelines.

Manual on Uniform Traffic Control Devices (MUTCD)

The MUTCD (FHWA 2012) "is a compilation of national standards for all traffic control devices, including road markings, highway signs, and traffic signals." States are required to comply with the MUTCD's provisions or to adopt a state MUTCD that substantially conforms to the national manual. States can negotiate exceptions to specific aspects of the national MUTCD when developing their state manual—most of these are typically made to conform to state law or to specify particular devices not to be used within the state.

Many existing transit preferential strategies are explicitly allowed in the MUTCD, including bus lanes, bus exemptions from turn restrictions, gates, TSP, and special transit signal indications (see the MUTCD summary in Appendix A for specific section references). Red pavement for bus lanes is expected to be added in the next edition of the MUTCD. Two strategies used internationally that are not specifically addressed in the MUTCD are pre-signals (signals used to manage queues and provide gaps for buses located upstream of a signalized intersection) and bus left-turn signals in combination with pedestrian crossing signals or beacons. The latter two strategies were the topic of additional study as part of TCRP Project A-39 and are discussed further in the "Innovative Strategies" section of Chapter 4 and in Appendix E.

Strategy-Specific Guidance

Several transit preferential strategies have been the subjects of comprehensive research projects, including bus lanes, TSP, curb extensions, roadway shoulder use by buses, and shared bus and bicycle lanes. Considering this strategy-specific material in combination with the comprehensive references described above, the TCRP A-39 researchers concluded that a strong base of standards and guidance for the geometric design (e.g., lane widths) exists for most commonly used transit preferential strategies.

Interagency Partnership Guidance

A key focus of TCRP Project A-39 was to identify effective practices for cooperation between roadway agencies, transit agencies, and other stakeholders when planning, designing, and operating transit preferential strategies. Identified documents included intergovernmental agreements (IGAs) and memoranda of understanding (MOUs), a study of inter-agency coordination needs for different elements of BRT systems, and two guides from the United Kingdom that address agency collaboration when implementing transit preferential strategies.

TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds (Boyle 2013) presented the results of a survey transit agencies in the U.S. and Canada on strategies they have used to improve bus speeds. The four most common reasons that agencies did not implement desired strategies were:

- Rider opposition (e.g., requiring a longer walk to a bus stop),
- Lack of roadway agency cooperation (e.g., allowing bus lanes or providing TSP),
- Community opposition (e.g., removing on-street parking, relocating a stop), and
- Lack of funding.

The TCQSM provides the following guidance on inter-agency partnerships:

> "Where there has been a strong policy directive to improve the role of public transit in accommodating a community's travel needs, preferential treatments should be implemented with transit agency and traffic engineering agency staff working in a coordinated manner. Measures should be cost-effective and should consider both long-term changes to mode split and the potential for attracting new riders. Both of these factors may be difficult to quantify. In most cases, bus preferential treatments will be more acceptable to roadway users and decision-makers when improvements to transit operations do not create undue traffic disruptions. However, in a policy environment favoring transit usage over private automobiles, 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.
>
> "In situations where the policy direction is not as clear or the inter-agency working relationships are not as strong, an incremental approach to developing preferential treatments may be more successful. This approach could involve demonstration projects that have a good potential for success and could be used to develop support for broader transportation improvement projects in the future."

Findings related to establishing partnerships with stakeholders included:

- Outreach should include an education element, as stakeholders may focus on the perceived disbenefits of the strategy to them and may not be aware of the benefits a strategy will provide.
- Establishing a good working relationship with roadway agencies is essential when considering strategies (e.g., bus lanes, TSP) that impact roadway infrastructure. At the same time, the synthesis identified a number of successful transit operations strategies that a transit agency can undertake themselves.
- Quantifying the outcomes of an implemented strategy can help build the case for future, possibly more challenging, implementations.
- High-level management support is essential, but it is also useful to involve all departments within the transit agency.
- Keep focused on the long-term objective and recognize that there will be challenges and opposition to overcome in the short term.

Case Studies

A number of papers and reports quantified the outcomes of specific applications of transit preferential strategies and had not been included in the more-comprehensive reports discussed above. Details are provided in Appendix A.

Literature Review Findings

Design Guidance

Standards and guidance for the geometric design (e.g., lane widths) of transit preferential strategies are relatively well-established, with information available in the AASHTO Transit Guide, various NCHRP and TCRP reports, and some transit agency design guidelines.

Warrants for Implementation

Warrants for implementing a number of strategies are provided in various NCHRP and TCRP reports; all of these warrants can be traced back to the 1970s-era *NCHRP Report 155.* Recent guidance, including the AASHTO Transit Guide, Canadian guidelines (Corby et al. 2013), and the TCQSM 3rd Edition, suggest considering a broad range of factors when considering transit preferential strategies, and many documented implementations have been undertaken with bus volumes well under the *NCHRP Report 155* warrants.

Analytical Tools

The TCQSM provides analytical methods for estimating the re-entry delay associated with bus stops when curb extensions are not present, and for estimating bus speeds on various types of bus facilities under various conditions (e.g., signal timing, traffic blockage). Its methods can also be adapted to estimate the speed benefit resulting from TSP. Appendix B to *TCRP Report 26: Operational Analysis of Bus Lanes* (St. Jacques and Levinson 1999) provides a more-detailed method for evaluating the effects of traffic signal progression and dwell time on bus speeds. Hunter (2000) and Liu, Zhang, and Cheng (2008) present analytical approaches for estimating the effect of TSP on bus speeds. No analytical approach was identified for estimating effects of transit-supportive roadway treatments on reliability. Case studies of TSP applications note that in many cases, the largest perceived benefit comes from reduced travel time variability, rather than reduced travel time. Smith, Hemily, and Ivanovic (2005) discuss the potential role of simulation in evaluating TSP.

Several agencies have developed methods or tools for identifying or prioritizing transit preferential treatments at specific locations. These include Hillsborough Area Regional Transit (HART) in Tampa, Florida (Danaher et al. 2006), New Jersey DOT (Hedden 2009), and the New Zealand Transport Authority (Harvey, Tomecki, and Teh 2012).

Difficulty of Quantifying Individual Strategy Benefits

While the literature does provide examples of quantified delay reductions and travel speed improvements—and, in rare instances, reliability improvements—associated with transit preferential strategy implementations, little of it is useful for TCRP Project A-39. In many cases, strategies have been implemented in conjunction with operational improvements or other infrastructure strategies, making it hard to separate out the effects of an individual strategy. In other cases, relevant background information is not available to help interpret the results. For example, the literature indicates that the quality of the existing signal timing plays a role in the amount of benefit derived from TSP implementations. Finally, when results are available for an individual strategy, they are usually reported on the basis of an entire route or corridor. As a result, it is not possible in these cases to determine whether each treated location contributed more-or-less equally to the overall result, whether specific locations provided the majority of the benefit, or even whether specific locations worked against the desired objective.

Relative Impact of Transit Operations and Traffic Engineering Strategies

The literature indicates that operational improvements (e.g., increased stop spacing, off-board fare payment) often provide the majority of the time or speed benefit when multiple strategies are implemented at the same time. *TCRP Synthesis 110* (Boyle 2013) notes that "successful agencies emphasized good ideas above technology. TSP and other traffic engineering actions topped the 'wish list' of responding agencies, but most of the successful actions could be implemented without new or added technology" (or infrastructure).

Approaches to Developing Agency Partnerships

Key findings of the documents related to interagency partnerships include:

- Interagency cooperation and effective communication are critical to the successful planning, design, and implementation of transit preferential strategies that involve roadway infrastructure and technology.
- The ability of transit systems to integrate into mainstream transportation operations and work with existing traffic networks is critical for the success of transit.
- Standards should be established for the application of strategies relying on technology (e.g., TSP) to allow a variety of users to communicate using equipment produced by a variety of manufacturers.
- Stakeholders should be involved early and an overall plan developed to successfully implement a transit preferential strategy.
- Performing a traffic analysis of the effects of a proposed strategy helps engage traffic engineering staff (i.e., quantifying roadway performance for a specific location or corridor will be received better than qualitative reports of how a treatment has performed elsewhere).

AGENCY INTERVIEW SUMMARY

Overview

Interviews were held with transit and roadway agency staff in U.S. and Canadian cities at two points during the project, focusing on (1) identifying processes used to develop interagency partnerships and (2) documenting unpublished benefits of transit preferential strategies. Three other interviews were conducted in response to panel member requests;

two to obtain the perspectives of bicyclists, and one with Sweden's third-largest city, Malmö, as the city has a well-established process for interagency cooperation for implementing transit projects. This section presents the overall findings from these interviews. Appendix B provides summaries of each interview.

Regions were selected on the basis of (1) having implemented transit-supportive roadway treatments, (2) geographic variety, and (3) to the extent possible, region size variety. A lead contact was identified at either the transit agency or a roadway agency in each region. The research team worked with the lead contact to identify appropriate staff at other agencies to invite to the interview, and to schedule one-hour interviews. To the extent possible, all participating staff were interviewed at the same time, but schedule conflicts made it necessary to conduct individual interviews in some cases. Some agencies were re-interviewed later in the project to dig deeper into their partnership processes. Appendix C lists the interview participants and provides the questions that were covered during the initial and follow-up interviews.

Table 6 lists the cities and regions interviewed, the agency types represented in each interview, and main project(s) or topic(s) addressed by the interview.

Table 6. Interview Participant and Topic Summaries

City, Region, or Organization	Agencies Participating in Interview	Topics
Columbus, Ohio	Transit agency	Multi-jurisdictional BRT corridor
Dallas, Texas	Transit agency	Introduction of TSP to a city
Eugene, Oregon	Transit agency	Multi-jurisdictional BRT corridors
Jacksonville, Florida	Transit agency State DOT	Conversion of a parking lane to a bus lane on a state highway
Los Angeles, California	Transit agency	Large-scale BRT implementation on surface streets, freeway BRT project
Malmö, Sweden	City transportation dept.	Transit preferential spot treatments, BRT corridor project, formal interagency partnership process
Minneapolis, Minnesota	Transit agency State DOT	Formal interagency partnership process
New York, New York	Transit agency City DOT	Select Bus Service projects
Ottawa, Canada	Transit agency	Transit preferential spot treatments
Portland, Oregon	Transit agency City transportation dept.	Addition of light rail to downtown bus mall
Salt Lake City, Utah	Transit agency	Multi-jurisdictional BRT corridor
San Francisco, California	Transit agency	Citywide transit preferential treatment program
Seattle, Washington	Transit agency Seattle DOT Suburban city	Multi-jurisdictional BRT corridor
Spokane, Washington	Transit agency	Bus stop consolidation program
Vancouver, Canada	Transit agency Provincial DOT Suburban city	Developing interagency partnerships in a region with many jurisdictions

League of American Bicyclists	Policy director	Bicyclist concerns when implementing transit preferential treatments
National Association of City Transportation Officials	Bikeway design guide project manager	Bicyclist concerns when implementing transit preferential treatments

Note: Dept. = department, DOT = department of transportation.

Agency Interview Findings

The following is a list of successful approaches used by the interviewed agencies to establish partnerships and implement transit preferential projects. The types of approaches used, and the degree to which they are used, will depend on the scale of the project, but approaches that appear to be generally applicable to any size project are listed in *italics.* The project's Guidebook drew from this information when its guidance matching specific approaches to specific project types and sizes was developed.

Identifying Projects

- Local and regional transportation planning processes can be used to identify both specific, larger-scale projects (e.g., BRT corridors) and to designate priority transit corridors where transit speed and reliability will be prioritized. The planning process can help develop an initial consensus among transportation agencies on the need for, and value of, transit preferential strategies. Having a project identified in a transportation plan is often a pre-requisite for grant funding.
- Bus drivers are a good source of information on locations where buses are frequently delayed.
- Identify upcoming roadway projects (e.g., paving, water, sewer, access management) and seek out opportunities to incorporate transit-preferential elements as part of the project.
- Prioritize high-ridership corridors first, as providing preference to transit will be easiest to justify in these corridors and will benefit the largest number of passengers.
- Prioritize easier-to-implement corridors first (e.g., wide streets, one-way operation, unused road capacity), as it is easier to make the case that transit preference can be provided without unduly affecting other road users. These corridors may also lend themselves to projects that benefit multiple modes.
- Transit operational improvements (e.g., stop consolidation, off-board fare payment) have fewer agency coordination needs than infrastructure projects, can be relatively low cost, and often provide the majority of the travel time and reliability benefits.
- Transit operational improvements on an important route, in combination with easier-to-implement roadway improvements, can be the recipe for a successful first project.

- Get most of the job done for less money than trying to fix everything at once for a lot of money. Consider phasing projects where some elements will be more controversial or can't be done within the available initial project.
- Research whether local traffic laws or agency design practice will need to be modified in order to use a specific transit preferential strategy.

Establishing and Maintaining Agency Partnerships

- High-level support within transit and roadway agencies is essential for getting things rolling. High-level political support can also be a catalyst on the roadway side.
- Good coordination between agency staff at lower levels, and a good transit agency working relationship with the construction project manager, is essential for a successful project.
- Establishing formal and regular meetings between transit agencies, roadway agencies, and stakeholders, helps to foster a culture of working together, which makes many projects possible.
- In states where the state highway system frequently includes urban arterials, state DOTs can be partners in project identification, funding, and construction.
- In a multi-jurisdictional environment, start with the jurisdictions that are the most receptive to working with you.
- Bringing money to the table goes a long way toward getting transit agency projects and needs prioritized by other stakeholders.
- Seek out win–win project features that can benefit the roadway agency or other stakeholders (e.g., sidewalk improvements, bicycle lanes, fiberoptic cable installation, TSP capabilities for the fire department).
- Successful projects build relationships among staff that help smooth the way for the next project.
- In large transit agencies with a sufficient number of capital projects to support the position(s), consider hiring staff with traffic engineering expertise. In addition, or as an alternative, help fund a position in a key roadway agency that is partially or fully dedicated to coordinating transit-focused projects.
- Consultants frequently work with, and have established relationships with, a number of public agencies and can help in reaching consensus in groups representing a variety of viewpoints.
- Conducting a traffic analysis helps convince traffic engineers that a proposed strategy will work as intended in a specific location. More-complicated strategies may require microsimulation.
- Educating stakeholders about transit's needs (for example, by taking stakeholders on a bus tour of a corridor, or by explaining the economics of providing bus service and how it differs from roadway projects) can help them understand the transit agency's perspective.

- When considering a new strategy that has never before been implemented in the transit agency's city or region, educating other agency staff can be important. Techniques, depending on the scope and scale of the strategy, could include providing guidebooks such as this one, study tours of successful implementations elsewhere, lending equipment used for TSP, and others.

Communication

- Communicate with project stakeholders early, often, and clearly.
- Communication includes providing information, receiving input, building consensus, and marketing.
- Project communication needs, depending on the scale of the project, can range from one-on-one meetings with individual to coordination meetings involving key agency staff, to large public meetings and workshops.
- Don't underestimate the number of meetings that may be required—corridor-scale projects may require over 100 meetings from planning through post-implementation.
- Meet with stakeholders at times and places that work for them. For example, business owners may prefer to meet early in the day, at their business, or both.
- Personal contact by key project staff with key stakeholders (e.g., the transit agency project manager during planning, the construction project manager during implementation) helps build rapport and identify specific concerns.
- Expect to have to educate stakeholders about technical aspects of the project. Minimize the amount of technical jargon used in stakeholder communications.
- Public meetings provide opportunities to show concepts and listen to concerns. A workshop format, with small breakout groups, may encourage more participation and discussion than a presentation-only, question-and-answer format.
- For projects involving a longer timeframe from planning to implementation, periodically revisit the list of stakeholders, as conditions may have changed along the corridor (e.g., new businesses).
- Strategies involving changes to traffic control (e.g., bus lanes, bus signals) may require an accompanying public awareness campaign coinciding with the project opening. It is essential to involve law enforcement agencies, as they will need to be on-board with enforcing new traffic controls.
- For larger projects, a project charter can be used to establish the purpose of the project, and the roles and responsibilities of key stakeholder representatives. The charter can help bring new persons up to speed quickly when a representative needs to be replaced (e.g., after taking a job elsewhere).
- Develop formal agreements (e.g., IGAs, MOUs) with partner agencies that specify respective roles and responsibilities, including funding responsibilities, where appropriate. Make sure that responsibility for anything that could significantly affect

the long-term project success is covered in one agreement or another (e.g., repairs, snow removal, enforcement).

- Following implementation, follow up with key stakeholders to confirm that things are going as expected, promises have been kept, etc., to retain and build credibility for future projects.

Potential Challenges During Planning and Implementation

- Understanding how curb space is used (e.g., parking, deliveries, bicycles) is vital to bus/transit lane projects.
- When proposing TSP, be prepared to address concerns that general traffic, pedestrians, or both will be unduly affected.
- Transit lanes should be self-explanatory to the extent possible, for example, through the use of colored pavement and overhead signs.
- Be prepared to show some flexibility (e.g., regarding specific stop locations) that can address particular stakeholder needs without compromising the overall project objectives.
- Particularly for large projects, more time and budget will be required than initially expected to address unanticipated issues that arise during the course of the project.
- Architectural treatments that make projects look nice initially may create maintenance headaches in the future.

Policy Environments

- Many transit preferential strategies have been implemented that serve significantly fewer buses and passengers than *NCHRP Report 155* (Levinson, Adams, and Hoey 1975) warrants.
- Policy environments described in the interviews that went beyond the "reduce person delay" criterion typically expressed in the literature included:
    - A willingness to take lanes for transit (and bicycles) as long as acceptable traffic operations can be maintained along the corridor—more delay at an individual location may be OK if offset elsewhere.
    - A willingness to consider innovative strategies (e.g., red paint, pre-signals, anything requiring a variance from roadway design standards).
    - A willingness to implement strategies as long as sufficient capacity was available.

Follow-up Evaluations of Projects

- It is uncommon for transit agencies to conduct follow-up evaluations of the effects of the treatments they implement. Reasons included lack of resources and the difficulty of separating out individual treatment effects when a package of improvements was implemented.

Bicyclist Perspective

- Bicyclists would prefer to have a separate bicycle facility (e.g., bicycle lane, cycle track) on higher-volume or higher-speed roadways than share a lane with buses.
- The interactions of buses and bicycles at bus stops have to be carefully thought out.
- Many transit preferential strategies (e.g., shorter traffic signal cycle lengths, turn exemptions/prohibitions) also benefit bicyclists.
- Studying whether signal timing optimized for buses would also benefit bicyclists would be of interest to bicycle stakeholders.
- The narrowest lane width that works for transit is desirable, as it leaves the most right-of-way available to make pedestrian and bicycle improvements.
- Shared bus/bike lanes, while not the ideal solution, may be preferable than the "before" condition, where buses, trucks, autos, and bikes would compete for the same space.

Innovative Treatments Not Addressed in the Literature

- Bi-directional, single-lane bus lane through signalized intersections (Salt Lake City).
- Bus left-turn opportunity in conjunction with a signalized pedestrian crossing (Ottawa).
- Double-cycling left-turn phases to serve bus left-turns (Ottawa).
- Transit lane located between through lane and left-turn lane at signalized intersections (Malmö).
- Reversible, peak-direction bus lane (Lund, Sweden).

Assessment

A common theme was the need for regular communication between transit and roadway agencies, to help staff understand each other's needs, to develop relationships and trust from working together, and to work together to address joint transportation issues. Regular communication can have pay-offs beyond a single project, such as in day-to-day transit operations (e.g., planning for construction detours).

Several interviewees from both transit and roadway agencies acknowledged that not all roadway agency staff are open to transit-supportive roadway projects. In roadway agencies with progressive leadership, this was addressed by "siloing" those staff to work on projects where they didn't have to deal with transit. In other cases, the roadway agency culture gradually evolved. Transit agencies found success in working with individual agency staff or (in multi-jurisdictional environments) jurisdictions who were open to transit improvements. One transit agency interviewee commented that "working with engineers isn't hard—just give them data and talk objectively, they want a smart solution."

Many initial projects arose from taking advantage of opportunities that came up—for example, roadway projects that could incorporate transit features or the availability of grant funding. In these cases, having a project already identified and in a local or regional transportation plan helped. Other projects took advantage of "low-hanging fruit," where it was not particularly difficult to implement transit-supportive treatments, a project benefitted a large number of transit passengers, or both. Transit operational improvements were usually implemented in conjunction with physical improvements and the operational improvements often provided the majority of the transit benefit. Nevertheless, including the physical improvements as part of the overall project allowed agency staff and roadway users to gain experience with them and build support for future implementations.

Depending on the local driving culture, enforcement can be an important ingredient for successfully implementing some types of transit-supportive treatments. Close coordination with the appropriate law enforcement agency (as early as the initial planning stage, as law enforcement may not be willing to enforce something they haven't been consulted on) is essential when enforcement will be required.

KNOWLEDGE GAPS

The following are key knowledge gaps relating to transit preferential strategies that were identified through the review of the state of the practice:

- How bus stop location, dwell time, dwell time variability, and traffic signal location and timing influence the effectiveness of various strategies. In particular, determining whether or not the effect of a treatment will be lost at the next traffic signal. Another issue to consider is that signal timing plans usually change during the day, meaning that treatment effectiveness may also change during the day. Two documents in the literature, Appendix B to *TCRP Report 26* (St. Jacques and Levinson 1997) and Skabardonis (2000), provide starting points for further investigation.
- More-specific information on the travel time and travel time reliability benefits of various strategies, eliminating the confounding effects of other actions (e.g., signal retiming, stop consolidation).
- Developing guidance on using (or not using) innovative treatments that were not addressed in the documents included in the U.S. literature review:
  - Pre-signals: signals placed in advance of a signalized intersection to manage traffic on the intersection approach
  - Bi-directional bus lane operation
  - Special bus phases to allow unusual turning movements
  - Center bus lanes to the right of left-turn lanes
  - Double-cycling phases used by transit
  - Bus-only links
  - "Shadowing" treatments: using upstream traffic signals or pedestrian beacons to create gaps in traffic so that buses can make turning movements with less delay

Chapter 3. Research Approach

At the conclusion of Phase I of the project, involving the literature review and agency review tasks described in Chapter 2, the research team developed a draft work plan for the remainder of the project. This work plan identified a set of potential research efforts designed to (1) fill gaps in knowledge identified during the first phase of the project and (2) address the other project objectives identified in Chapter 1. The research team discussed the work plan with the project oversight panel, with the panel selecting specific research tasks to be addressed during Phase II, working within the available research budget. The research efforts selected by the panel were divided into two main groups of tasks: (1) Collect and Analyze Data, and (2) Standards and Guidance Modifications. Each of these tasks was divided into several subtasks, each addressing a specific research objective.

This chapter describes the approach taken to each subtask. Chapter 4 presents the key findings and recommendations that resulted from this work.

TRANSIT SIGNAL PRIORITY IMPACT ASSESSMENT

Background

The impacts of TSP vary depending on their design and traffic characteristics (e.g., intersection geometry, presence of queue jump lanes, presence of exclusive lanes, traffic volumes and patterns), transit characteristics (e.g., service frequency, bus stop location), signal control system features and timings (e.g., cycle length, green times), and TSP features (e.g., minimum green extension, red truncation, rules for granting priority). The literature review summarized in Chapter 2 showed that the implementation of TSP strategies can result in lower delays for buses and vehicles that travel in the same directions, but can have negative impacts on the delays of the cross (i.e., non-priority) streets. The magnitude of this negative impact varies from insignificant delay increases to major ones, especially when the cross-streets operate close to saturation.

The assessment of TSP strategies has been mainly based on simulation and field studies. Simulation studies are data-intensive and, as a result, time-consuming (Rakha and Zhang 2004, Ahn and Rakha 2006). In addition, most of these studies do not accurately incorporate TSP logic and features, and thus fail to realistically model the TSP systems. Field tests typically have high costs (i.e., equipment, extra delays to traffic during the experiment), are time consuming, and the findings cannot be easily generalized because they depend on the study site characteristics (Ahn, Rakha, and Collura 2006). Analytical models offer a straightforward and less data-intensive approach for assessing TSP. Existing analytical models (Sunkari et al. 1995; Liu, Zhang, and Cheng 2008) ignore random and oversaturation delays. As a result, they cannot accurately estimate the impact of TSP when conditions are close to or over saturation, which is the case for non-priority approaches that operate close to saturation. Other analytical approaches summarized in the literature (e.g., Kittelson & Associates, Inc., et al. 2007) focus on the benefits of TSP on the priority movements during one signal priority cycle.

Objective

This objective of this subtask was to develop an analytical approach for estimating the impacts of TSP at signalized intersections, using the analysis procedures given in the *Highway Capacity Manual 2010* (HCM 2010), building upon a methodology developed in an earlier project (Christofa and Skabardonis 2011).

Approach

The subtask involved the following steps:

- Develop the theory for applying the HCM 2010 to estimate the impacts of TSP at signalized intersections.
- Test the theory using a simulation model of a real-world intersection where TSP has been implemented.
- Evaluate progression requirements and constraints for maximizing the benefit of TSP.

POLICY THRESHOLD DEVELOPMENT

Background

As described in Chapter 1, the general philosophy expressed by guidance literature on transit preferential strategies has been that these strategies are warranted when overall person delay is reduced. However, the experiences related in the interviews and the case study literature indicate that strategies have been implemented in many situations where bus volumes were relatively low and negative operational impacts to general traffic likely occurred. In these cases, a policy environment existed that deliberately favored transit operations over general traffic operations. The literature review also identified that the most recent guidance (e.g., the draft AASHTO Transit Guide, Canadian guidelines [Corby et al. 2013], and the TCQSM 3rd Edition) all identify the need to consider a broad range of factors when considering transit preferential strategies.

This review indicates that a one-size-fits-all approach to providing guidance on when to consider transit preferential strategies may not fit need the needs of the users of the guidance. Different transit agencies may operate in communities where different policy environments exist, and regional transit agencies may experience a variety of policy environments across their service areas. Therefore, one approach to providing guidance in this project's Guidebook would be to define multiple policy environments and to provide different guidance (e.g., minimum bus/person volumes) for each environment. This approach would allow transit and roadway agencies to quickly determine the conditions that would support implementing a particular strategy, given the existence of a particular policy environment.

Examples of possible policy environments include the following:

- *Maintain or reduce person delay.* Under this environment, a strategy would be warranted if the overall delay reduction for bus passengers outweighed any delay increase for other roadway users.
- *Allow small increases in auto delay.* This approach recognizes that the delay experienced by a given motorist at a given intersection varies from one day to the next and, therefore, small increases in average delay are not perceived by motorists. Under this environment, a strategy would be warranted if the change in auto delay would be within the normal range of daily variation in delay.
- *Use available capacity.* In many jurisdictions, developments are not required to make roadway improvements unless the additional traffic generated by the development would cause roadway operations to exceed the jurisdiction's operations (e.g., level of service) standards. Under this environment, a strategy would be warranted as long as the jurisdiction's minimum operations standard was maintained.
- *Prioritize transit service.* This approach maintains minimal traffic operations (i.e., operations below capacity) and necessary land use access, and makes safety a priority for all modes. This policy environment would permit any transit preferential strategy that can fit within these constraints.

Objective

The objective of this subtask was to test combinations of factors appropriate to the strategy being tested (e.g., traffic volumes, bus and passenger volumes, traffic signal timing) using software implementing *Highway Capacity Manual* methods, to determine the feasibility for developing general guidance or specific warrants tailored to specific policy environments.

Approach

This subtask was to include the following work elements:

- Further analysis of warrants and recommendations from the literature;
- Developing a spreadsheet to assess the impact of transit preferential treatments on *Highway Capacity Manual* outputs such as delay, level of service, and volume-to-capacity ratio; and
- Developing preliminary policy guidance for practitioners based on the literature review, survey, interviews, and spreadsheet.

Work was begun on the spreadsheet, but as results came in the simulation study, it became clear that it would be impractical to develop guidance appropriate for every possible situation, given the wide range of traffic volumes, bus volumes, roadway geometry, signal timing, and policy environments possible. In addition, the final AASHTO Transit Guide generally avoided the use of warrants in favor of more flexible decision-making criteria.

Therefore, work on this task was stopped, as it did not appear that it would result in useful information that could be incorporated into the Guidebook.

STRATEGY EVALUATION USING AVL DATA

Background

The literature review and agency interviews described in Chapter 2 identified that more information was needed on the specific speed and reliability impacts of individual strategies. In many cases, multiple strategies were implemented at the same time, which made it difficult or impossible to isolate the effects of specific strategies. In other cases, limited budgets constrained agencies' abilities to perform before-and-after evaluations.

Objective

The objective of this subtask was to identify transit agencies that (1) had implemented specific transit preferential strategies in isolation and (2) had detailed AVL data available to permit a retrospective before-and-after analysis of the effects of the implementation. For the purposes of this subtask, the AVL data needed to be detailed enough that (1) data were available from most buses during the before-and-after periods and (2) bus arrival and departure times were known at specific locations in sufficient detail that before-and-after delay could be accurately determined at an intersection level.

Approach

Several candidate transit agencies were identified from research team contacts and the interview results. OCTranspo (Ottawa, Canada) had offered to provide AVL data during their interview, but the research team determined that their data was insufficiently detailed to be useful for this work. TriMet (Portland, Oregon) was represented on the panel and offered to provide data, but was unable to identify a suitable project where a strategy had been implemented in isolation. However, King County Metro (Seattle, Washington) did have the necessary combination of detailed AVL data and a project where strategies were implemented in series.

One set of AVL data provided by King County Metro was for a transit lane implementation on Aurora Avenue in Seattle from N 46th Street to N 145th Street as part of the E Line RapidRide. Four scenarios were assessed:

- Scenario 1: October 2012 and June 2013 baseline conditions,
- Scenario 2: October 2013 Business Access and Transit (BAT) lanes implementation,
- Scenario 3: December 2013 traffic response timing implementation, and
- Scenario 4: March 2014 three-door boarding implementation, plus schedule modifications.

The AVL data were used to assess bus travel time differences between each scenario.

A second set of AVL data was provided from a TSP implementation on the C Line Rapid Ride in West Seattle. Average signal delay for nine intersections along the corridor was evaluated with and without TSP operating.

SIMULATION STUDY

Background

The literature review and agency interviews described in Chapter 2 identified that more information was needed on the specific speed and reliability impacts of individual strategies beyond that found in published and unpublished documents. The agency interviews did not identify any upcoming isolated strategy implementations within TCRP Project A-39's timeframe that could be used to conduct field studies of changes in bus speed and reliability. Furthermore, as described for the previous subtask, there were only a few projects identified that (1) had been implemented in isolation of other transit preferential strategies and (2) for which detailed AVL data were available that would permit a before-and-after analysis. Therefore, simulation was identified as the only practical way to test the impacts of specific strategies in specific locations on bus and general traffic operations.

An advantage of simulation is the ability to control multiple variables, including their interaction. However, a key factor for achieving realistic results is using a model that can accurately represent actual field conditions, including actual bus schedules, bus dwell times and dwell time variability, pedestrians, and specific strategies.

Objective

The objective of this subtask was to measure the change in intersection operational performance metrics as a result of different transit preferential strategies. The simulation model provides an experimental laboratory to incrementally adjust parameters and examine how buses and general traffic respond to those adjustments. The effort aimed to find answers to the following questions:

- Do buses benefit from a particular strategy? Under what conditions?
- How is general traffic affected by a particular strategy and what is the magnitude of the effect?
- Do the effects of strategies vary under different traffic volumes?
- Do the effects of strategies vary with different bus headways?

Approach

To save the time and cost involved in building and calibrating a simulation model, an existing calibrated model developed for a real-world project was desirable. The researchers had access to a number of these. Seven of these were presented to the panel for consideration, and three were selected for further study. The project's time and budget constraints resulted in one of these three models being used for this subtask. The following summarizes the key aspects of the research approach; details are provided in Appendix D.

The selected model was an existing calibrated VISSIM model of a portion of Broward Boulevard in Fort Lauderdale, Florida. In the first stage of the testing, a portion of the model was used, representing a 1,500-foot section of the corridor centered on a single intersection. An intersection-level analysis was initially conducted to capture variations in traffic volumes, bus stop locations, bus headways, and preferential treatments. The performance measures assessed included average delay for the total intersection, mainline and side street approach; level of service for the overall intersection; average travel time along the mainline; and queue lengths.

After the completion of the intersection-level model runs, a corridor-level analysis was conducted, using the full 1.3-mile length of the street covered in the model (see Figure 1). The model contains ten intersections (numbered in the figure); nine of these are signalized. Traffic is progressed in the eastbound direction (toward downtown Ft. Lauderdale) during the time period modeled. The cycle length is 160 seconds, with the eastbound through movement receiving green for an average of 56% of the cycle (i.e., a g/C ratio of 0.56), while the westbound through movement has an average g/C ratio of 0.49.

Source: Aerial photo © 2014 Google.

Figure 1. Broward Boulevard Corridor

Several fundamental assumptions were incorporated into the model:

- The experimental zone would be bounded by untreated intersections (i.e., the intersections at the ends of the modeled corridor [#1 and #10 in the figure] would not be modified with any transit preferential strategies).
- All traffic signals would be modeled using the PTV RBC signal controller.
- No lane restrictions would be imposed on buses.
- Any changes in signal timing would not allow minimum pedestrian walk and clearance times to be violated.

Intersection-Level Scenarios

At the intersection level, the transit preferential strategies were applied to a single intersection, NW 7th Avenue, to identify their effects at a point location. For this level of analysis, three intersections were selected in order to isolate the treatment effects at the test intersection: NW 9th Avenue, NW 7th Avenue, and NW 5th Avenue.

NW 9th and NW 5th Avenues served as entrances to the model on the arterial and were not modified. NW 7th Avenue was selected as the subject intersection because it offered heavier side-street volumes, which were suspected to experience greater impact when the various strategies were applied. Table 7 summarizes the scenarios investigated for the intersection-level analysis.

Table 7. Intersection-Level Analysis Scenarios

Scenario	Description
Existing operations, near-side	No changes to signal timing/phasing; test stop location near-side.
Existing operations, far-side	No changes to signal timing/phasing; test stop location far-side.
Queue jump, near-side	Program queue-jump into signal timing on arterial (both directions); test stop location near-side.
Queue jump, far-side	Program queue-jump into signal timing on arterial (both directions); test stop location far-side.
Queue bypass lane	Install queue bypass lane at intersection along arterial, and locate stop far-side along bypass lane.
TSP, near-side	Program advanced signal TSP along arterial (both directions); test stop location near-side.
TSP, far-side	Program advanced signal TSP along arterial (both directions); test stop location far-side.
TSP, near-side, pedestrian recall	Program advanced signal TSP along arterial (both directions); test stop location near-side. This scenario also enables pedestrian recall on all approaches.
TSP, far-side, pedestrian recall	Program advanced signal TSP along arterial (both directions); test stop location far-side. This scenario also enables pedestrian recall on all approaches.

The scenarios described in Table 7 served as the treatment-related differentiators between variables to test. In addition to the variation in treatments, the effects of congestion levels (three levels) and bus frequency (three levels) were also considered across all scenarios. As a result, each variation in a given treatment is tested through nine scenarios (each volume and each headway scenario), resulting in 81 scenarios.

Corridor-Level Scenarios

For the corridor-level analysis, the focus shifted from variables regarding headways and stop locations to the effects of where TSP is implemented along a corridor. Specifically, the analysis was performed with the following question in mind: *Which intersections should be treated with TSP?* Table 8 summarizes the corridor scenarios that were developed.

Table 8. Corridor Scenarios

Scenario	Description
Existing operations	Existing volumes, no TSP
Major intersections	TSP at major intersections, $v/c \geq 0.9$
Medium intersections	TSP at medium intersections, $0.6 < v/c < 0.9$
Minor intersections	TSP at minor intersections, $v/c \leq 0.6$
All intersections	TSP at all intersections
All intersections, 2-minute headways	TSP at all intersections, 2-minute bus headways

Note: v/c = volume-to-capacity ratio.

The 2-minute headway scenario was modeled to see the most extreme condition where TSP would be provided at all intersections and there would always be a bus to take advantage of the TSP operation. The scenario was originally modeled as 1-minute bus headways, but caused buses to back up on each other. Using 2-minute headways allowed for increased bus frequencies without the issue of exaggerated delay and queuing at stop locations.

Simulation Process

All intersection and corridor scenarios were run 30 times each, using a unique traffic seed value for each run to produce a distribution of results. An individual scenario "run" is a total of 90 simulated minutes, broken into the following periods:

1. *15-minute warm-up period.* This period allows the model to be fully populated with traffic and for traffic signals to start up and run the expected timings.
2. *60-minute data collection period.* This is the time period where all performance measures are captured.
3. *15-minute stabilization period.* This time ensures that traffic is present continuously until the end of the data collection period.

After the runs were completed, performance metrics were analyzed for traffic during the 60-minute data collection period for all traffic, non-transit traffic, and buses individually. The collected performance metrics focused on:

- Approach delay,
- Overall intersection delay, and
- Arterial travel time.

Pedestrian delay for these analyses was not specifically analyzed. However, pedestrian delay is expected to be unaffected by the tested TSP treatments for the following reasons:

- Any geometric changes to the intersection for different scenarios did not affect pedestrians' crossing distance or path.
- No operational treatment used violated minimum pedestrian phase timing or omitted the pedestrian walk or flashing don't walk intervals.
- While the MUTCD (FHWA 2009) allows for the omission of a pedestrian walk interval as long as the associated vehicular phase is also omitted or the pedestrian phase is exclusive (see MUTCD Section 4D.27, Preemption and Priority Control of Traffic Control Signals), these options were not used. No signal timing was programed to omit any pedestrian phase and no signal timing was programed to reduce any pedestrian times.

The corridor-level analysis was modeled with real-world pedestrian volumes at intersections. These inputs were in the model to appropriately capture any additional delay to turning vehicles.

INNOVATIVE STRATEGIES

Background

The literature review and agency interviews described in Chapter 2 identified a number of transit preferential strategies used internationally that have not been widely used to date in the United States (or used at all). It is not known whether this lack of use is due to the unsuitability of the strategies in a U.S. context, a lack of information about whether the strategies are allowed by the MUTCD or other national guidelines and standards, a lack of knowledge of their benefits, or some combination of these factors. The agency and stakeholder interviews also indicated a need for improved guidance on addressing bus–bicycle conflicts in bus lanes and at bus stops, which affects a wide variety of strategies.

Objective

The primary objective of this subtask was to identify international practice in applying innovative transit preferential strategies, to evaluate their applicability in a U.S context, and (if appropriate) recommend guidelines for their U.S. The secondary objective was to review current U.S. and international practice on addressing bus–bicycle conflicts and to develop recommendations based on this practice.

Approach

Promising Strategies

The following promising strategies were investigated:

- *Bus pre-signals:* Traffic signals installed on one direction of a street in advance of a signalized intersection, used to manage queues at the intersection and to provide priority for buses travelling in a bus lane, when conditions make it impractical to continue the bus lane all the way to the intersection.
- *Bus-only links:* Short sections of roadway that can only be used by transit vehicles and other authorized vehicles (e.g., emergency vehicles).
- *Special bus phases:* A signal phase included in the traffic signal cycle to serve bus movements that cannot be served concurrently with other traffic (e.g., a left turn from a right-side bus lane).
- *Traffic signal shadowing:* A technique where a bus at an unsignalized intersection triggers a call for a phase at a nearby signalized intersection; when that phase is served, a gap in traffic is created that allows the bus to complete its turn.
- *Bus boarding islands:* Bus stops on raised concrete islands within the roadway, used to provide bus stops in locations where a conventional stop would be difficult to provide (e.g., left-side bus lanes, intersections with right-turn channelizing islands).

An international literature review was conducted to identify standards and guidelines for each strategy, along with documented benefits, disbenefits, and implementation sites. The MUTCD and AASHTO Transit Guide were also consulted to identify guidance relevant to each strategy. Based on this information, each strategy was evaluated with respect to its suitability for implementing in the U.S., including describing important considerations when considering applying the strategy. Strategies evaluated to be potentially appropriate, but possibly requiring changes to current U.S. practice to be usable in the U.S., were passed on to the next two subtasks (MUTCD Modifications and AASHTO Transit Guide Modifications) for additional work.

Managing Bus and Bicycle Interactions

This portion of the work identified and evaluated the various techniques used in the U.S. and internationally for managing bus and bicycle interactions. The work included a review of leading U.S. and international guidance documents on bicycle facilities.

MUTCD MODIFICATIONS

Background

As discussed in Chapter 1, a project objective was to "identify potential changes to the *Manual on Uniform Traffic Control Devices* (MUTCD) and related documents to facilitate implementation of selected strategies." The Innovative Strategies subtask, described above, identified strategies deemed to be potentially applicable in a U.S. context that required further study to determine whether they were allowed by the MUTCD, or would require a change to the MUTCD to be usable.

Objective

The objective of this subtask was to identify whether revisions to the MUTCD would be required to allow selected innovative strategies to be used in the United States. There were several possible outcomes of each review:

- The strategy was not prohibited by the MUTCD and required no further action to be applied.
- The strategy was not currently allowed by the MUTCD, but was expected to be added in the next edition of the MUTCD. Experimentation request templates would be prepared for strategies falling into this category.
- The strategy was not currently allowed by the MUTCD, but did not receive significant opposition when discussed with the appropriate technical committee of the National Committee on Uniform Traffic Control Devices (NUTCD). Draft MUTCD language would be prepared for strategies falling into this category, along with a document providing supporting information.
- The strategy was not currently allowed by the MUTCD and received significant opposition when discussed with the NUTCD. These strategies would be recommended for further study, but no further work would be done with them as part of TCRP Project A-39.

Approach

Members of the research team attended appropriate NUTCD technical subcommittee meetings in January and June 2014 to make brief presentations about TCRP Project A-39, provide information about selected innovative strategies, and solicit feedback on the strategies. The research team also discussed the selected strategies directly with the FHWA staff responsible for the corresponding MUTCD chapters.

AASHTO TRANSIT GUIDE MODIFICATIONS

Background

The AASHTO Transit Guide was being finalized as TCRP Project A-39 was being conducted. This guide has been in development for more than ten years. An interim version of the guide was published in July 2002 as the product of an NCHRP project (Fuhs 2002). A follow-up project, TCRP D-09 (Transit Vehicles and Facilities on Streets and Highways) produced an updated version in 2007. During the balloting process for the 2007 guide, inconsistencies were noted between the guide and the then-current AASHTO Green Book. Furthermore, an update to the Green Book was planned. Therefore, the Transit Guide was put on hold until the Green Book was updated, so the Transit Guide content could be aligned with the Green Book. A third project in 2012, NCHRP 20-07 Task 296, made these alignment changes to the Transit Guide. The final version of the guide was published in July 2014.

Objective

The objective of this subtask was to review AASHTO Transit Guide content relevant to transit preferential strategies and to recommend changes for a future edition, drawing from the new information developed by TCRP Project A-39.

Approach

The researchers reviewed a draft copy of the Transit Guide in mid-2013 that had gone through one round of balloting with state Design Engineers. The researchers then re-reviewed the guide in mid-2014 after the final version was published and developed recommendations for material to be changed or updated in a future edition.

Chapter 4. Findings and Applications

Chapter 3 previously described the work tasks undertaken during Phase II of TCRP Project A-39 to (1) address gaps in knowledge identified at the end of Phase I and (2) address other project objectives. This chapter summarizes the findings from each of these tasks and, where appropriate, describes potential applications of the work. The appendices to this report provide additional details on how the work was conducted.

TRANSIT SIGNAL PRIORITY IMPACT ASSESSMENT

The *Highway Capacity Manual 2010* (HCM 2010) is commonly applied by traffic engineers to estimate average vehicle delay at intersections, given a set of input conditions, including traffic demands by approach and movement, intersection geometry (e.g., number and width of lanes), and signal timing characteristics. In this subtask, the HCM's signalized intersection method was used to estimate cross-street delay with and without the provision of TSP (green extension or red truncation) and to evaluate whether or not TSP granted at an upstream intersection would be wasted at the next downstream intersection, due to the bus arriving on red. Details are provided in Appendix C.

Cross-Street Delay Estimation

The ratio of *cross-street delay with TSP* to *cross-street delay without TSP* can be used to develop delay adjustment factors. These factors, when multiplied by the HCM's delay estimate without TSP, estimate the cross-street delay that would occur during traffic signal cycles when TSP is provided. The use of such factors allows for the quick estimation of delays on cross-streets and the evaluation of TSP strategies without the need for intensive additional calculations or time-consuming simulations.

The adjustment factors are applied using the following equation:

$$d_{cs} = d_{cs,NoBus}[1 + P(\text{bus})(f_{TSP} - 1) \qquad (1)$$

where

d_{cs} = average cross-street delay (seconds per vehicle);

$d_{cs,NoBus}$ = HCM estimate of cross-street delay in cycles without a bus arrival (seconds per vehicle);

$P(\text{bus})$ = probability of a bus arrival during a given cycle = the cycle length divided by the average two-directional bus headway, both in seconds; and

f_{TSP} = cross-street delay adjustment factor from Table 9 through Table 12.

Table 9 through Table 12 provide adjustment factors for volume-to-capacity (v/c) ratios of 0.6, 0.7, 0.8, and 0.9; effective green–to–cycle length (g/C) ratios of 0.35, 0.40, 0.45, and

0.50; cycle lengths from 70 to 120 seconds; and priority intervals (i.e., green extensions or red truncations) of 5 and 10 seconds.

Table 9. HCM Delay Adjustment Factors for v/c =0.60

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	1.36	*3.25*	1.35	*2.36*	1.34	*2.08*	1.34	*1.81*
80	1.27	*2.05*	1.28	*1.85*	1.29	*1.75*	1.30	*1.74*
90	1.24	*1.74*	1.24	*1.63*	1.25	*1.60*	1.26	*1.60*
100	1.21	*1.56*	1.21	*1.51*	0.99	*1.50*	1.23	*1.52*
110	1.18	*1.46*	1.18	*1.43*	1.19	*1.43*	1.21	*1.45*
120	1.16	*1.39*	1.17	*1.38*	1.17	*1.38*	1.19	*1.40*

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

Table 10. HCM Delay Adjustment Factors for v/c =0.70

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	1.54	*5.57*	1.46	*4.10*	1.43	*3.24*	1.43	*2.73*
80	1.40	*3.48*	1.36	*2.74*	1.35	*2.25*	1.35	*2.09*
90	1.32	*2.61*	1.29	*2.10*	1.29	*1.91*	1.29	*1.81*
100	1.26	*2.00*	1.25	*1.78*	1.25	*1.67*	1.25	*1.64*
110	1.22	*1.75*	1.21	*1.60*	1.22	*1.56*	1.23	*1.54*
120	1.19	*1.57*	1.19	*1.49*	1.19	*1.46*	1.20	*1.47*

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

Table 11. HCM Delay Adjustment Factors for v/c =0.80

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	2.18	7.78	1.84	6.03	1.78	5.53	1.67	4.74
80	1.76	4.23	1.61	4.37	1.55	3.84	1.50	3.39
90	1.55	3.96	1.46	3.28	1.42	2.93	1.40	2.62
100	1.42	3.08	1.37	2.61	1.35	2.37	1.33	2.18
110	1.36	2.58	1.30	2.19	1.29	2.01	1.29	1.90
120	1.29	2.16	1.26	1.92	1.25	1.81	1.25	1.72

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

Table 12. HCM Delay Adjustment Factors for v/c =0.90

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	**3.07**	**8.60**	**2.77**	**7.33**	**2.61**	**6.73**	**2.43**	**6.18**
80	**2.49**	**6.23**	**2.28**	**5.52**	**2.14**	**5.05**	**2.04**	**4.73**
90	**2.13**	**4.95**	**1.97**	**4.37**	**1.87**	**4.05**	**1.80**	**3.79**
100	**1.88**	**3.98**	**1.73**	**3.55**	**1.69**	**3.33**	**1.64**	**3.15**
110	**1.69**	**3.37**	**1.59**	**3.01**	**1.57**	**2.88**	**1.52**	**1.78**
120	**1.39**	**2.53**	**1.51**	**2.66**	**1.47**	**2.49**	**1.44**	**2.38**

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

As an example of how to apply this equation, assume a traffic signal where the cycle length is 100 seconds, the average g/C ratio for the cross-street approach is 0.35 (i.e., slightly more than one-third of the total cycle length serves the approach), the v/c ratio for the cross-street approach is 0.80 (i.e., 80% of the approach's capacity is used), 6 buses per hour will be granted priority, and the HCM estimate of average signal delay for the approach, without priority, is 40.0 seconds per vehicle. Furthermore, assume that 10 seconds of priority (green extension or red truncation) are desired.

Because the v/c ratio is 0.80, Table 11 is used. The delay adjustment factor for the combination of a g/C ratio of 0.35, a 100-second signal cycle, and 10 seconds of priority is found to be 3.08.

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	2.18	7.78	1.84	6.03	1.78	5.53	1.67	4.74
80	1.76	4.23	1.61	4.37	1.55	3.84	1.50	3.39
90	1.55	3.96	1.46	3.28	1.42	2.93	1.40	2.62
100	1.42	$\boxed{3.08}$	1.37	2.61	1.35	2.37	1.33	2.18
110	1.36	2.58	1.30	2.19	1.29	2.01	1.29	1.90
120	1.29	2.16	1.26	1.92	1.25	1.81	1.25	1.72

The probability of a bus arriving in a given cycle is the cycle length (100 seconds) divided by the average headway between buses (3,600 seconds per hour / 6 buses per hour = 600 seconds), or 0.167.

Substituting the above information into Equation (1) produces the following:

$$d_{cs} = d_{cs,NoBus}[1 + P(\text{bus})(f_{TSP} - 1)]$$

$$d_{cs} = (40.0)[1 + (0.167)(3.08 - 1)] = 53.9 \; seconds$$

Therefore, over the course of an hour, the cross-street is estimated to experience approximately 14 seconds per vehicle additional delay as a result of TSP. This result can be translated into hourly person-delay by multiplying by the result by the hourly volume of vehicles on the approach and by an assumed vehicle occupancy. The result can be compared to the estimated change in bus delay, applying the results from the Simulation

Study subtask described later in this section, to obtain a quick, conservative estimate of the impact of TSP on delay. (The estimate is considered conservative because potential delay reductions to major-street traffic are not calculated.)

Equation (2) below can be applied in combination with the HCM to obtain a more-precise estimate of the change in general traffic delay, considering both the cross street and the main street. In lieu of applying an adjustment factor, the HCM methodology is used directly to estimate average delay by approach when priority is granted. The signal timing parameters input to the HCM method are adjusted to reflect the desired priority interval (e.g., a green extension of 10 seconds).

$$d_{cs} = d_{cs,Bus} P(\text{bus}) + d_{cs,NoBus} P(no\ bus) \tag{2}$$

where

$d_{cs,Bus}$ = cross-street delay in cycles with a bus arrival (seconds per vehicle),

P(no bus) = probability of no bus arrival during the cycle (decimal) = 1 – P(bus), and

all other variables are as described previously.

The advantages of Equation (2) over Equation (1) are that it allows the change in major-street delay to also be estimated, no interpolation is required, a broader range of input parameter values can be provided, and any signal timing that the HCM accommodates can be applied. The key disadvantage is that the HCM signalized intersection methodology has to be applied twice, instead of once.

Signal Progression Effects on Retaining TSP Delay Benefits

The time saved by granting priority to a bus at a traffic signal will be lost at the next downstream signal if the bus arrives on red and has to wait for the downstream signal to turn green to proceed. In these cases, the time saved at the upstream signal is converted into extra delay at the downstream signal, as the bus arrives earlier than it would have otherwise, but departs at the same time it would have without priority (Skabardonis 2000). Consequently, simply summing "typical" delay savings due to TSP at individual intersections along a corridor may overestimate the net savings achieved over the length of a corridor.

Equations (2) and (3) provide a simple check on whether priority granted at one signalized intersection is likely to be wasted at the next downstream signal, for the cases of red truncation and green extension, respectively. If the condition expressed by these equations is not satisfied, the TSP benefit is likely to be wasted.

$$O_2 \le (O_1 - \tau) + (L/V_B) + D_B \le O_2 + g_2 \tag{2}$$

$$O_2 \le (O_1 + g_1 + \tau) + (L/V_B) + D_B \le O_2 + g_2 \tag{3}$$

where

O_1 = offset at the upstream intersection (seconds),

O_2 = offset at the downstream intersection (seconds),

τ = priority (e.g., red truncation) interval (seconds),

g_1 = green time at the upstream intersection (seconds),

g_2 = green time at the downstream intersection (seconds),

L = distance between signals (feet),

V_B = bus running speed (feet per second) = speed in miles per hour × 1.47, and

D_B = bus delay between intersections (seconds) = sum of dwell time(s), re-entry delay(s), and acceleration/deceleration delays at bus stops between the two signals.

The components of bus delay—average dwell time, average re-entry delay (i.e., delay waiting for a gap in traffic when leaving the stop), and acceleration/deceleration delay—can be measured in the field or estimated using procedures given in the TCQSM (Kittelson & Associates, et al. 2013).

Equations (2) and (3) hold for undersaturated (i.e., under capacity) traffic conditions along the arterial, with no residual queues at the downstream intersection and all arriving vehicles being able to discharge during the same signal cycle. The equations also assume no congestion along the arterial link to significantly affect bus speeds. The equations are applied to pairs of intersections along a corridor in evaluating whether priority granted at the upstream intersection of a given pair will be lost at the downstream intersection.

These equations are especially useful in situations where the signal settings (offset and green times) cannot be adjusted. This situation can arise, among other reasons, because an intersection is the critical intersection in the arterial bandwidth, because two coordinated arterials meet at the intersection, or because high volumes exist on all intersection approaches.

A key assumption for Equations (2) and (3) is that each bus experiences the same amount of delay (i.e., identical dwell times, identical re-entry delays) between the two signalized intersections. However, this is unlikely to be the case, except when no bus stops are provided between the two traffic signals. For example, a rule-of-thumb given in the literature (St. Jacques and Levinson 1997, Kittelson & Associates et al. 2013) is that 95% of dwell times will be less than or equal to twice the average dwell time (i.e., the standard deviation of dwell times is 60% of the average dwell time). Therefore, these equations indicate whether or not TSP will be wasted for a bus experiencing average delay, but do not guarantee that any given bus will be able to take advantage of the priority.

If the standard deviation of dwell times is known (e.g., from AVL data) or assumed (e.g., using default values from the TCQSM), the percentage of buses able to benefit from priority can be estimated using the following procedure.

Let m_L represent the difference between O_2 and the middle term of Equation (2) or (3), represents how much shorter dwell times can be at a bus stop located between the intersections, compared to average, and still have the bus arrive at the downstream intersection just as the signal turns green. Similarly the difference between $O_2 + g_2$ and the middle term of Equation (2) or (3), or m_U, represents how much longer dwell times can be, compared to average, and still have the bus arrive at the downstream intersection before the signal turns red. Assuming the dwell times are normally distributed, statistical tables or a spreadsheet's normal distribution function can be used to calculate the percentages of buses with dwell times shorter than the average by m_L seconds, and longer than average by m_U seconds. These two groups of buses will experience no net delay benefit from TSP, as they will arrive on red at the downstream intersection. The remaining buses will receive a net benefit, as they will arrive on green.

For example, assume that O_2 is 70 seconds, the middle term of Equation (2) or (3) results in a value of 80 seconds, and the value of $O_2 + g_2$ is 100 seconds. Therefore, m_L is -10 seconds and m_U is +20 seconds. Furthermore, assume that the average dwell time is 30 seconds and that the standard deviation of dwell times is 60% of the average dwell time, or 18 seconds. From the normal distribution, 29% of buses will have dwell times shorter than (30-10) seconds, while 87% of buses will have dwell times shorter than (30+20) seconds. Therefore, 29% of buses would arrive before the signal turns green, while 13% of buses would arrive after the signal turned red; neither group would benefit from TSP at the upstream intersection. The remaining 58% of buses would benefit.

Finally, the bus delay benefit calculated for the upstream intersection should be multiplied by 58%, in consideration that the net change in delay experienced by 42% of the buses traveling from the upstream intersection to the downstream intersection will be zero.

STRATEGY EVALUATION USING AVL DATA

E Line Rapid Ride

Transit preferential strategies for King County Metro's E Line Rapid Ride were implemented in three stages:

- A business access and transit (BAT) lane (i.e., a bus lane allowing right-turning traffic) opened in October 2013,
- Traffic-responsive signal timing was implemented in December 2013, and
- Three-door boarding and schedule modifications (headway changes) were implemented in March 2014.

AVL data were provided by King County Metro for periods following the implementation of each strategy, as well as for baseline periods in October 2012 and June 2013. Bus travel times through the 5-mile corridor were determined for each direction between 6 a.m. and 7 p.m. Minimal travel time differences were observed between baseline and BAT lane or between baseline and BAT lane plus traffic-responsive signal timing. However, travel times did improve and became more consistent following the implementation of three-door boarding and headway modifications, as shown in Figure 2.

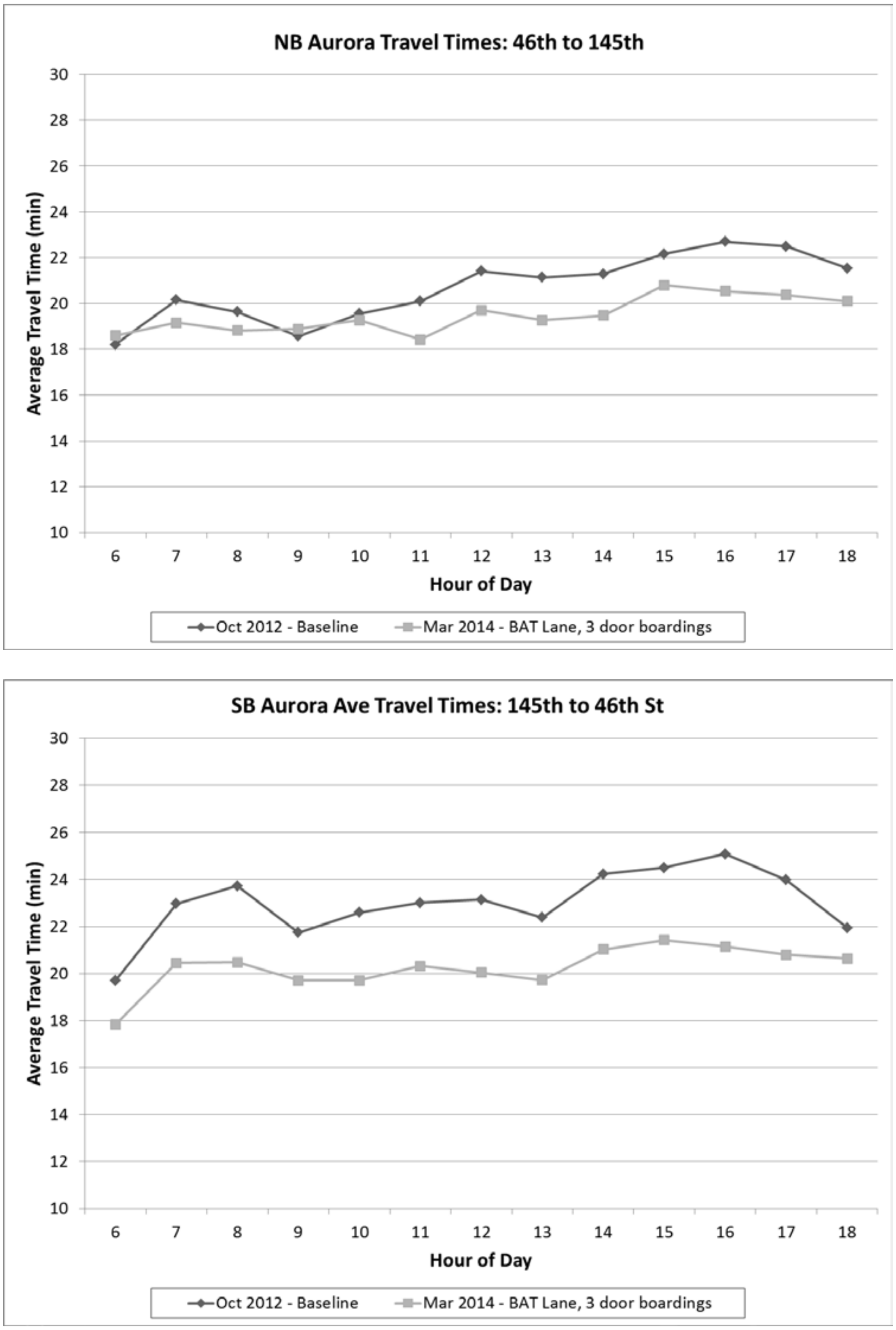
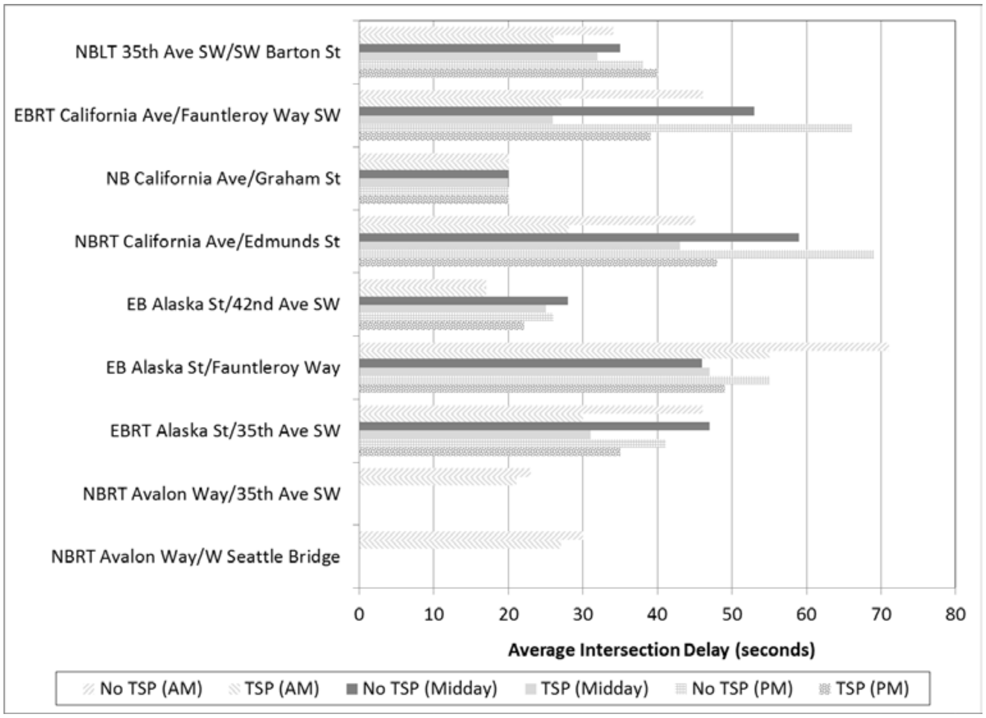


Figure 2. Overall Change in RapidRide E Line Travel Time from Baseline to Full Implementation

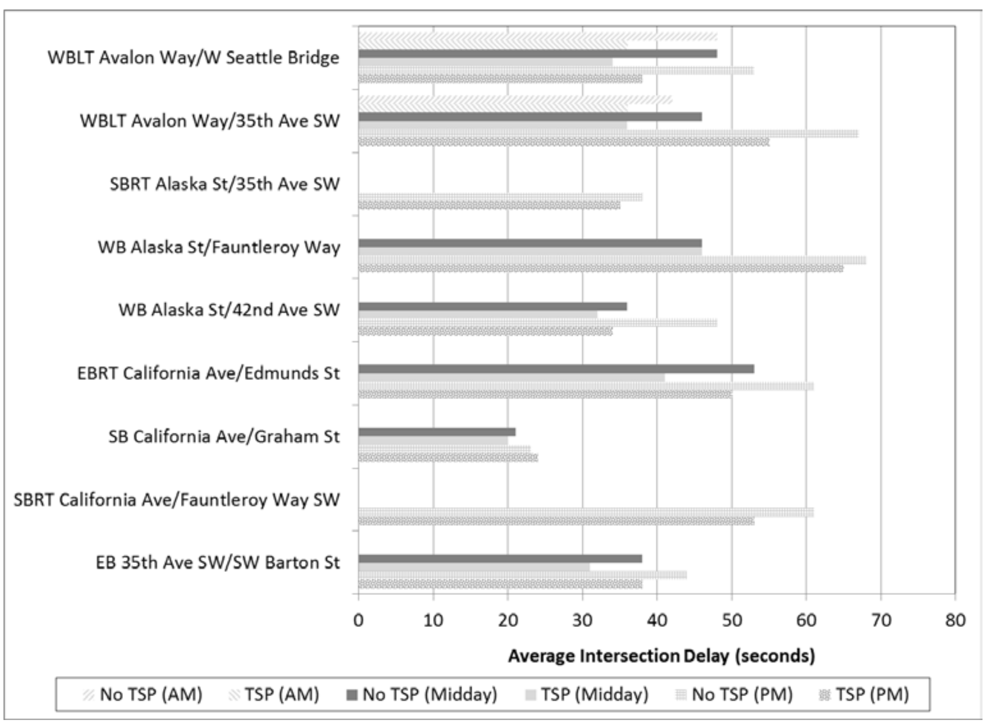
As shown in Figure 2, northbound times ranged from 18 minutes to 22.5 minutes, depending on the time of day, under baseline conditions, and from 18.5 minutes to 21 minutes after full implementation. Travel times improved in all hours studied, except two, with the best improvements of about 2 minutes occurring in the afternoon, when the northbound direction is the peak direction. In the southbound direction, travel times ranged from 19.5 to 25 minutes under baseline conditions, and from 18 to 21.5 minutes after full implementation (19.5 to 21.5 minutes if the 6 a.m. hour is excluded). Travel times improved during all hours; during the peak and midday time periods, travel times improved by 2–3.5 minutes. Travel times in both directions were more consistent after full implementation. These results are consistent with other studies discussed in Chapter 2, in that the majority of the travel time benefit was provided by the operational strategies.

C Line RapidRide

King County Metro provided data on average traffic signal delay at nine intersections, with and without TSP, during a.m. peak, midday, and p.m. peak periods. In the northbound direction, average delay was reduced considerably (16–27 seconds) in 9 of the 23 combinations of intersection and time period, reduced slightly (1–9 seconds) in 8 combinations, unchanged in 4 combinations, and increased slightly (1–2 seconds) in 2 combinations. In the southbound direction, delay was reduced considerably (10–15 seconds) in 8 of the 18 combinations, reduced slightly in 8 combinations, unchanged in 1 combination, and increased by 1 second in 1 combination. Figure 3 shows the results by direction, intersection, and time period.



(a) Northbound



(b) Southbound

Source: King County Metro

Figure 3. Average RapidRide Line C Intersection Delay With and Without TSP

SIMULATION STUDY

Many implementations of transit preferential strategies documented in the literature have implemented multiple changes at once, including but not limited to, relocating bus stops, optimizing signal timing, and changing bus stop spacing. In most cases, as a result, it has not been possible to isolate the specific impact of an individual strategy. The simulation study subtask was designed to address this issue by evaluating the effects of selected strategies both in isolation and in combination.

As introduced in Chapter 3, the simulation effort was divided into two main work efforts: (1) an evaluation of specific strategy impacts at a single intersection, and (2) the cumulative effects of strategies when implemented along a corridor. This section summarizes the results from this subtask; Appendix D provides details of the effort.

Intersection-Level Results

Table 13 presents the average travel time to traverse a 1,500-foot section of the study arterial, centered on the study intersection, for both (1) buses and (2) all vehicles (buses and non-buses) on the arterial approaches to the study intersection. The table also shows the average intersection delay for all vehicles entering the intersection, including cross-street vehicles, under the base-case combinations of stop location (near-side or far-side) and volume-to-capacity (v/c) ratio (0.5, 0.8, and 1.0). As many of the subsequent tables present the effects of various strategies in terms of percentage changes in travel time and delay, it should be noted that a 1% change in bus travel time corresponds to a change of approximately 1.8–2.0 seconds, depending on the scenario, a 1% change in all-vehicle travel time corresponds to a change of approximately 0.4–0.5 seconds, and a 1% change in intersection delay corresponds to a change of approximately 0.25–0.4 seconds.

Table 13. Intersection-Level Travel Time and Delay Results (Base Case)

	Travel Time (s)		Average
Stop Location (v/c = 0.5)	**Arterial Vehicles**	**Buses**	**Intersection Delay (s)**
Near-side	39.2	181.2	24.5
Far-side	38.6	178.8	23.9
	Travel Time (s)		**Average**
Stop Location (v/c = 0.8)	**Arterial Vehicles**	**Buses**	**Intersection Delay (s)**
Near-side	43.2	187.4	31.7
Far-side	42.6	183.9	30.5
	Travel Time (s)		**Average**
Stop Location (v/c = 1.0)	**Arterial Vehicles**	**Buses**	**Intersection Delay (s)**
Near-side	49.9	199.4	41.2
Far-side	49.8	190.6	38.5

Note: v/c = volume-to-capacity ratio.

As expected, arterial travel times and average intersection delay both increased as traffic volumes (v/c ratio) increased. Table 13 also shows that travel times and average delay were consistently lower when far-side stops were used than when near-side stops were used. The reason for the large bus travel time is that the section included an upstream bus stop that was used to generate random bus arrivals at the study intersection. The upstream bus stop used an average dwell time of 90 seconds, with a standard deviation of 50 seconds.

Table 14 compares the difference in travel time and average delay for each tested strategy at each v/c level, relative to the base case of a near-side stop. The following results can be observed from the table:

- The greatest travel time benefit for both arterial vehicles resulted from the combination of moving the stop to the far side of the intersection and adding TSP in one direction only. Arterial vehicle travel times through the intersection improved by 3.3% to 5.5% (corresponding to 1–3 second reductions in travel time), while bus travel times improved 3.3% to 7.4% (corresponding to 6–15 second reductions in travel time). Overall intersection delay was reduced by 1.6% to 5.3% (0.2–2.2 seconds).
- Moving the stop from near side to far side had approximately the same impact on bus travel times as implementing TSP.
- Queue jumps with a near-side stop, as expected, consistently increased arterial vehicle travel times (as the green time for the queue jump was taken from the arterial green time). They only produced a meaningful benefit to bus travel time at a v/c ratio of 1.0.
- Queue jumps in conjunction with a far-side stop produced modest improvements to both arterial vehicle travel times (because buses no longer blocked the right traffic lane when a far-side bus pullout was provided) and bus travel times (because they could get through the intersection a little faster than previously by using the right-turn lane).
- The best improvements to overall intersection delay resulted from moving the bus stop to the far side, providing TSP in on direction along the arterial, and calling the cross-street pedestrian phase (thereby providing a longer cross-street green) after serving a TSP request. Although the ped recall function benefitted cross-street traffic and reduced overall intersection delay, it also diluted the travel time benefits to bus traffic and resulted in higher arterial vehicle travel times.

Table 14. Intersection-Level Results, Compared to Near-Side Stop Base Case

Strategy (v/c = 0.5)	% Change in Travel Time: Arterial Vehicles	% Change in Travel Time: Buses	% Change in Average Intersection Delay

Move stop to far-side	-1.5	-1.3	-2.4
Add TSP (both directions)	-1.4	-1.5	+1.6
Add TSP (one direction)	-1.1	-1.5	+1.2
Add queue jump	+2.8	NS	+2.0
Move stop to far-side and add queue jump	-1.8	-1.4	-2.9
Move stop to far-side and add TSP (both directions)	-2.3	-3.1	-0.8
Move stop to far-side and add TSP (one direction)	-3.3	-3.3	-1.6
Move stop to far-side and add TSP (one direction, ped recall)	+5.8	NS	-4.9
	% Change in Travel Time		**% Change in**
Strategy (v/c = 0.8)	**Arterial Vehicles**	**Buses**	**Average Intersection Delay**
Move stop to far-side	-1.3	-1.8	-3.8
Add TSP (both directions)	-1.4	-1.5	+3.8
Add TSP (one direction)	-2.7	-1.7	-1.9
Add queue jump	+4.9	-0.8	NS
Move stop to far-side and add queue jump	-2.2	-2.5	-4.4
Move stop to far-side and add TSP (both directions)	-2.3	-4.1	-0.6
Move stop to far-side and add TSP (one direction)	-3.9	-4.2	-5.0
Move stop to far-side and add TSP (one direction, ped recall)	+2.8	-1.6	-13.2
	% Change in Travel Time		**% Change in**
Strategy (v/c = 1.0)	**Arterial Vehicles**	**Buses**	**Average Intersection Delay**
Move stop to far-side	NS	-4.6	-6.6
Add TSP (both directions)	-2.6	-4.0	NS
Add TSP (one direction)	-4.3	-5.2	NS
Add queue jump	+5.5	-3.4	+2.6
Move stop to far-side and add queue jump	-2.2	-5.3	-8.0
Move stop to far-side and add TSP (both directions)	-2.6	-7.4	-5.8
Move stop to far-side and add TSP (one direction)	-5.5	-7.4	-5.3
Move stop to far-side and add TSP (one direction, ped recall)	+1.5	-5.3	-7.8

Notes: v/c = volume-to-capacity ratio, TSP = transit signal priority.
NS = not a statistically significant effect (alpha=0.05).

Compared to providing TSP in both directions, providing TSP in only one direction resulted in better travel time benefits both for buses and all arterial vehicles. Additionally, when the stop was moved to the far side, adding TSP in one direction tended to equalize the travel time benefit for buses and all vehicles.

Table 15 compares the difference in travel time and average delay for each tested strategy at each v/c level, relative to the base case of a near-side stop. The following results can be observed from the table:

- When a far-side stop already existed, adding TSP improved bus travel times by 1.8% to 3.3% (3–6 seconds). Providing TSP in both directions provided similar benefits to buses as providing TSP in one direction, but reduced the all-vehicle travel time benefits by more than one-half. Overall intersection delay generally increased when TSP was added, but the maximum increase in average delay was on the order of 1 second. Providing TSP in one direction only tended to equalize the travel time benefit between non-buses and buses on the arterial.
- Queue jumps in combination with an existing far-side stop consistently increased all-vehicle travel times and overall intersection delay, and provided a statistically significant bus travel time benefit at a v/c ratio of 1.0.

- Queue jumps produced small travel time and delay benefits for all vehicles.

Table 15. Intersection-Level Results, Compared to Far-Side Stop Base Case

Strategy (v/c = 0.5)	% Change in Travel Time Arterial Vehicles	 Buses	% Change in Average Intersection Delay
Add TSP (both directions)	-0.8	-1.8	+1.7
Add TSP (one direction)	-1.8	-2.0	+0.8
Add TSP (one direction, ped recall)	+5.9	+1.3	-2.5
Add queue jump	+3.0	NS	+3.8
Move stop to far-side and add queue jump	-0.3	NS	-0.4
Strategy (v/c = 0.8)	**% Change in Travel Time Arterial Vehicles**	** Buses**	**% Change in Average Intersection Delay**
Add TSP (both directions)	-1.1	-2.3	+3.3
Add TSP (one direction)	-2.7	-2.4	-1.3
Add TSP (one direction, ped recall)	+2.9	+0.3	-9.8
Add queue jump	+6.6	NS	+4.6
Move stop to far-side and add queue jump	-0.9	-0.6	-0.7
Strategy (v/c = 1.0)	**% Change in Travel Time Arterial Vehicles**	** Buses**	**% Change in Average Intersection Delay**
Add TSP (both directions)	-2.4	-3.1	NS
Add TSP (one direction)	-5.3	-3.1	+1.2
Add TSP (one direction, ped recall)	+1.5	-0.9	-1.3
Add queue jump	+6.2	-1.0	+10.1
Move stop to far-side and add queue jump	-2.0	-0.9	-1.6

Notes: v/c = volume-to-capacity ratio, TSP = transit signal priority.
NS = not a statistically significant effect (alpha=0.05).

Corridor-Level Results

Unlike the intersection-level analysis, the overall corridor was not modeled at high, medium, and light traffic demand levels. Instead, the various intersections along the corridor were used to provide a cross section of v/c ratios. Additionally, bus headways for all corridor-level scenarios were set at 5 minutes, except for one where the headways were set at 2 minutes. This was approach was taken to model a transit-heavy corridor, and thereby analyze results from a relatively extreme situation.

Figure D-5 presents average intersection delay by scenario. For all traffic, average intersection delay was lowest for the *Existing* and *Minor Intersections* scenarios, and was highest for the *2-minute Headway* scenario. The average intersection delay for *2-minute Headway* was 11% greater than that of the *Existing* scenario, and the average intersection delay for *Minor Intersections* was virtually equivalent to that of the *Existing* scenario. Overall, there was only a 2-second difference between the highest and lowest scenario delays.

INNOVATIVE STRATEGIES

Appendix C presents the results of the innovative strategies evaluation. In addition, a summary was developed of best practice for managing bus and bicycle interactions at and between bus stops, as bicyclists are an important stakeholder group to work with when implementing transit-supportive roadway strategies. This summary is provided as Appendix C of the Guidebook.

MUTCD MODIFICATIONS

The research team attended several National Committee on Uniform Traffic Control Devices (NCUTCD) meetings over the course of the project, and interacted with FHWA staff with specific questions on transit-supportive roadway strategies being considered for the Guidebook. The following sections discuss identified transit-supportive roadway strategies that were definitely or possibly not allowed by the current MUTCD, and the feedback the research team received regarding these strategies.

Colored Pavement Markings for Public Transit

Consultant staff attended the Markings Technical Committee (MTC) meeting in June 2014 at which colored pavement markings were discussed. The MTC discussed colored pavement markings within the context of developing a response to FHWA's recommended rewrite of Part 3 (Markings) for the next edition of the MUTCD (likely to be 2017). Related to colored pavement markings, the FHWA had proposed a new section, numbered 3H.07, to cover the use of red colored pavement markings for public transit systems. The FHWA-proposed new language read:

Section 3H.07 Red Colored Pavement for Public Transit Systems (FHWA Proposal)

Support:

01 Red colored pavement is used to enhance the conspicuity of locations, station stops or travel lanes in the roadway exclusively reserved for vehicles of public transit systems or multi-modal facilities where public transit is the primary mode. These public transit vehicles include buses, taxis, streetcars, trolleys, light-rail trains, and rapid transit fleets.

Option:

02 Red colored pavement may be used where engineering judgment determines that one or more of the following conditions are expected to result in its application:

A. Increased travel speeds will be expected by the public transport vehicle after an exclusivelane or facility is provided,

B. Reduced overall service time through the corridor will be expected by the public transport vehicle,

C. The implementation of the red colored pavement to an existing general purpose lane in the traveled way will not adversely affect the traffic flow in the remaining general purpose lanes,

D. Decreased rates of illegal parking or occupation of the transit or multi-mode lane or facility will be expected.

Standard:

03 **If used, 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.**

04 **Regulatory signs (see Section 2B.XX) shall be used to establish the allowable use of the lane, area, or location. 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.**

Guidance:

05 *Red colored pavement should be retroreflective to distinguish it from non-retroreflective aesthetic treatments.*

Red colored pavement should not be used on public transit facilities separated from the roadway or on facilities on an exclusive alignment.

Standard:

06 **If colored pavement is used on travel lanes or facilities that allow bicycle use in addition to public transit vehicles, then the color shall be red. Such facilities shall not incorporate elements of green colored pavement.**

After discussion, the MTC took the following action on FHWA's proposal:

- Paragraph 01: Change from support to option, including word changes to "may be used". (Vote 26-0-0)
- Paragraph 02: Delete entire option. (Vote 26-0-0)
- Paragraph 03: Delete paragraph. (Vote 25-1-0)
- Paragraph 05: Delete paragraph. (Vote 20-0-0)

The updated text (previous paragraph numbers have been retained for cross referencing) as approved by MTC reads:

Section 3H.07 Red Colored Pavement for Public Transit Systems (MTC Recommendation)

Option:

01 Red colored pavement may be used to enhance the conspicuity of locations, station stops or travel lanes in the roadway exclusively reserved for vehicles of public transit systems or multi-modal facilities where public transit is the primary mode. These public transit vehicles include buses, taxis, streetcars, trolleys, light-rail trains, and rapid transit fleets.

Standard:

04 **Regulatory signs (see Section 2B.XX) shall be used to establish the allowable use of the lane, area, or location. 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.**

Standard:

06 **If colored pavement is used on travel lanes or facilities that allow bicycle use in addition to public transit vehicles, then the color shall be red. Such facilities shall not incorporate elements of green colored pavement.**

The research team concurs with the recommended changes from the MTC. The language as proposed allows the use of red colored pavement markings to designate public transit lanes while allowing flexibility in their application. The research team developed a Request for Experimentation template (included as Appendix D in the Guidebook) for use by agencies wanting to apply this strategy prior to its inclusion in the MUTCD.

Pre-Signals

The research team contacted the FHWA staff member responsible for Part 4 of the MUTCD (Highway Traffic Signals) regarding the use of advance signals for applications such as bus queue jumps or to facilitate downstream turning movements. The feedback received from FHWA staff is that there is nothing in the MUTCD that would prohibit the use of advance signals in a transit preferential treatment context. However, FHWA staff did indicate that if advance signals are used to provide transit priority, the indication shown to the transit vehicle should not conflict with the indication shown to general traffic (i.e., a green circular indication to the transit vehicle on the same approach as a red circular indication to general purpose traffic). Instead, the transit vehicle indication should be consistent with the light rail transit signal indications. This use of light rail transit signal indications is permitted in Section 4D.27, Paragraph 18 of the 2009 MUTCD.

Bus Signals in Conjunction with Hybrid Pedestrian Beacons

One idea that was raised during the course of the project was the potential use of providing bus priority in conjunction with hybrid pedestrian beacons (i.e., HAWK signals). This would essentially be a form of traffic signal shadowing, where a bus wishing to turn left onto or off of a busy street would trigger a call to the hybrid pedestrian beacon, which would stop traffic and create a gap in major-street traffic that could be used to make a turn.

The feedback the research team received at the NCUTCD meeting indicated that there would be strong opposition on the part of FHWA and the Signals technical committee to using hybrid pedestrian beacons in this way. Two potential concerns with this strategy are (1) hybrid beacons are not allowed within 100 feet of an existing intersection, so it would only be applicable to intersections where a downstream mid-block pedestrian crossing is provided, and (2) motorist respect for the pedestrian beacon might be degraded if they had to stop when no pedestrian was crossing.

The research also contacted transit agency staff in Ottawa and Vancouver about their use of bus signals in combination with pedestrian half-signals. The applications they identified involved facilitating left turns from a side street onto a major street, where the bus is detected on the side street, the pedestrian crossing phase is activated, and the bus can turn left while major street traffic is stopped (minor street traffic is STOP-controlled at these half-signals). (Edmonton also uses this kind of priority.) However, no applications were found involving left turns from a major street onto a minor street using pedestrian half-signals. The MUTCD does not permit pedestrian half-signals.

Finally, Calgary has installed a bus-only left-turn signal on a divided highway that stops opposing traffic when a bus arrives (Jordan et al. 2010). Through traffic traveling in the same direction as the bus is not signal-controlled. This arrangement is said to save 10–15 buses per hour an average of 90 seconds during peak periods, compared to the original situation of no signal and buses having to wait for a gap in traffic in the opposite direction. The bus volumes served in this case would be insufficient to meet any of the MUTCD's volume-based warrants.

Canadian guidelines (Corby et al. 2013) suggest using a transit signal installed specifically for buses in situations where creating a gap for left-turning buses is desired, although they note that practice varies across Canada in terms of whether local or provincial practice allows this strategy.

A potential solution for the U.S. is a proposed new MUTCD chapter on busway grade crossings, which would allow traffic signal control as an option to serve busway movements where a busway crosses another roadway at grade (NCUTCD 2014). The term "busway" was not explicitly defined in the proposed chapter at the time of writing, but it was stated that "the design and operation of a busway is similar to light-rail transit in a semi-exclusive alignment." Furthermore, bus-only lanes could comprise a busway. If busway is understood to mean any bus-only lane or off-street facility used exclusively by buses, then this proposed chapter would allow the installation of a traffic signal to serve bus movements from bus-only lanes. This would be a more straightforward way to address the transit need than a shadowing approach using hybrid pedestrian beacons; as the latter is simply a way to try to address the issue within the current MUTCD framework.

AASHTO TRANSIT GUIDE

The research team reviewed a draft version of AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets* in mid-2013 and re-reviewed it once the final version was published in mid-2014. The guide compiles best practice from a variety of sources and generally retains the tone and built-in policy assumptions of its source material. Thus, in some places, the guide can be behind current U.S. practice (e.g., applicable environments for TSP, bus volumes warranting particular treatments) when the source material was based on *NCHRP Report 155*, and ahead of current U.S. practice when the source material was more recent and international (e.g., colored bus lanes, pre-signals, bus-only links). The guide provides design recommendations for a wide range of transit-supportive roadway strategies and is even-handed in its discussion of them. Thus, the guide makes a good companion document for this project's Guidebook.

Nevertheless, there are some areas where the guide can be improved, typically as a result of more-recent research being published during the time the guidebook was under development. Specific suggestions for changes are as follows:

- Section 3.3 (Transit Quality of Service and Capacity Considerations). This section is based on the TCQSM 2nd Edition, but a 3rd Edition was published in 2013 and the section is recommended to be updated to reflect the latest TCQSM. In particular, the 3rd Edition changed some quality of service measures and did away with level of service letters in most cases; the bus capacity methods were also updated to incorporate the latest research.
- Section 4.1.4 (Bus Facilities on Limited Access Highways: General Guidelines): Table 4-2 presents specific bus volume guidelines for different kinds of bus facilities on freeways, based on *NCHRP Report 155,* assuming an average of 40 passengers per bus. This implies that nearly every seat is occupied on every bus, depending on the type of bus assumed to be using the lane (e.g., standard bus vs. motor coach vs. articulated bus), as transit agencies typically avoid having passengers stand during high-speed freeway operations. At the higher ends of the stated ranges, the passenger volumes on buses would typically exceed the number of drivers and passengers in a freeway lane. The table and accompanying guidance is much more limited in terms of the factors considered, relative to the urban street guidance.
- Section 5.1.2.1 (Community Densities): It is recommended that the densities should specify whether they are based on net acres (i.e., developed land only) or gross acres (i.e., actual area including streets, parks, and other supporting uses).
- Section 5.2.2.1.2 (Bus Stop Design Dimensions): It is recommended that Table 5-2 incorporate the additions made by the two most recent editions of the TCQSM.
- Section 5.2.2.2.1 (Bus Bulbs and Curb Extensions): The AASHTO guide's list of situations that are "not recommended" for transit is auto-centric. Conditions such as only one lane being available in the direction of travel, high bicycle traffic, or low pedestrian volumes may warrant further analysis or require additional design features, but should not by themselves disqualify a location from consideration. A cross-reference to Section 7.1.4.3 is recommended, where the benefits of curb extensions for pedestrians are described.
- Section 5.2.2.3 (Bus Bays): The auto traffic volume of 250–500 vehicles in the curb lane as a consideration for installing a bus pullout may not be necessary if a second lane is available for the traffic to merge into. A dwell time of 10 seconds is basically the time required to open the doors, serve one boarding passenger, and close the doors again; a dwell time of at least 20 seconds (comparable to a parking maneuver) is recommended to be considered, while *TCRP Report 19* suggested dwell times longer than 30 seconds as a justification for a pullout. Suggested additional factors for considering a pullout are (1) when the bus stop is a timepoint and (2) when no

opportunities are available for other vehicles to pass the bus over a sequence of several stops.

- Section 5.3.2.3 (Traffic Signal Control): It is recommended that the *Traffic Signal Timing Manual,* 2nd Edition be added to the list of guidelines on traffic signal timing and coordination. Later in this section, the example of 90 buses per hour vs. 40 vehicles per hour as a situation where traffic signals could be timed for buses is highly imbalanced in favor of the auto mode, particularly when considered on a person-delay basis. (It is also imbalanced when considered on a vehicle delay basis.) Still later, it is stated that "where bus volumes are high, it may be desirable to limit bus priorities to every other signal cycle." Other potential actions in this situation include retiming the signals to favor buses, or to limit signal priority to the peak direction only. Finally, there is no particular reason to limit queue jumps/bypasses to bus headways of 15 minutes or less, other than cost/benefit considerations, which are covered by a later bullet.
- Section 5.4.1 (Transit Priority Facilities: Planning Context): "There is little value in providing bus priority measures where service is poor, costly, or non-existent; where there is no congestion; or where the community does not want to maintain and improve bus service or to enforce bus lanes." Even when there is no congestion, it can be beneficial to transit agencies to provide priority measures that improve bus speeds and/or reliability. In addition, reserving road right-of-way for transit is easier before the roadway becomes congested than after. It is not apparent why "costly" bus service should not be provided with priority. The text in quotes above is derived from *NCHRP Report 155* (Levinson et al. 1975).
- Section 5.4.1 (Transit Priority Facilities: Planning Context): "There are two main types of arterials where transit priority should be considered: (1) high-speed (40-50 mph), high-standard suburban arterials; and (2) lower-speed, short-block, urban streets in downtowns and other areas with concentrated employment. Intersection (spot) treatments can be applied as stand-alone measures or in conjunction with the above types of corridors." Limiting priority measures to these types of streets dismisses opportunities to improve bus speed and reliability in other contexts and does not match U.S. practice.
- Section 5.5.7.5 (Advance Stop Bar for Bus Left Turn): It is recommended that the virtual bus lane and merge-assist applications of pre-signals be added to supplement the weave assist application described in this section.
- Section 5.8.1.1 (TSP: Principles): Related to the second-to-last paragraph, TSP does *not* require more than an adjustment to the following cycle to maintain coordination.

Chapter 5: Conclusions and Suggested Research

CONCLUSIONS

Design Guidance

Standards and guidance for the design (e.g., lane widths, traffic control) of transit-supportive roadway strategies are relatively well-established, with information available in the AASHTO Transit Guide (AAHSTO 2014), MUTCD (FHWA 2009), various NCHRP and TCRP reports, and some transit agency design guidelines. Therefore, this project's Guidebook relies on referencing existing design guidance, rather than presenting new guidance, except when no or minimal U.S. guidance existed.

Criteria for Implementing Transit-Supportive Strategies

Warrants specifying minimum bus volumes required to implement particular strategies have been provided in various NCHRP and TCRP reports; all of these warrants can be traced back to *NCHRP Report 155* (Levinson et al. 1975). More recent guidance, including the AASHTO Transit Guide, Canadian guidelines (Corby et al. 2013), and the TCQSM (Kittelson & Associates et al. 2013)—as well as the evolution of transportation engineering practice toward context-sensitive solutions and complete streets—suggests that a broader range of factors should be considered when evaluating potential strategies. In addition, this project's interviews and literature review found that many projects have been implemented with bus volumes well below the *NCHRP Report 155* warrants, particularly when implemented in conjunction with BRT projects. Therefore, this project's Guidebook avoids the use of warrants in favor of evaluating the project within the context of the local policy environment. The outcome of this approach is that environments that prioritize automobile operations will require higher bus volumes to implement a strategy than ones that prioritize transit operations. This approach also promotes the consideration of multiple factors and not just bus volumes.

Approaches to Developing Agency Partnerships

Key findings of the interviews and literature review related to developing agency partnerships for implementing transit-supportive roadway strategies are:

- Regular communication between transit and roadway agencies is essential, to help staff understand each other's needs, to develop relationships and trust from working together, and to work together to address joint transportation issues. Regular communication can have pay-offs beyond a single project, such as in day-to-day transit operations (e.g., planning for construction detours).
- Many initial projects arose from taking advantage of opportunities that came up—for example, roadway projects that could incorporate transit features or could take advantage of grant funding obtained by the transit agency. In these cases, having a project already identified and in a local or regional transportation plan helped. Other projects took advantage of "low-hanging fruit," where it was not particularly

difficult to implement transit-supportive treatments, a project benefitted a large number of transit passengers, or both. Transit operational improvements were usually implemented in conjunction with physical improvements and the operational improvements often provided the majority of the transit benefit. Nevertheless, including the physical improvements as part of the overall project allowed agency staff and roadway users to gain experience with them and build support for future implementations.

- Performing a traffic analysis of the effects of a proposed strategy in the specific context where it would be implemented helps engage traffic engineering staff (i.e., quantifying roadway performance for a specific location or corridor will be received better than qualitative reports of how a treatment has performed elsewhere). One transit agency interviewee commented that "working with engineers isn't hard—just give them data and talk objectively, they want a smart solution."
- Stakeholders should be involved early and an overall plan for stakeholder engagement developed to successfully implement a transit-supportive strategies.
- Several interviewees from both transit and roadway agencies acknowledged that not all roadway agency staff are open to transit-supportive strategies. In roadway agencies with progressive leadership, this was addressed by "siloing" those staff to work on projects where they didn't have to deal with transit. In other cases, the roadway agency culture gradually evolved. Transit agencies found success in working with individual agency staff or (in multi-jurisdictional environments) jurisdictions who were open to transit improvements.
- Depending on the local driving culture, enforcement can be an important ingredient for successfully implementing some types of transit-supportive treatments. Close coordination with the appropriate law enforcement agency (as early as the initial planning stage, as law enforcement may not be willing to enforce something they haven't been consulted on) is essential when enforcement will be required for a successful outcome.

Benefits of Transit-Supportive Roadway Strategies

One of the challenges faced by this project was that transit-supportive roadway strategies are frequently not implemented in isolation, but as packages of strategies. While this is generally a good approach to implementing strategies, as it increases the bus speed and reliability benefit, it does make it difficult to identify the contributions of the individual strategies to the overall outcome. Therefore, a particular focus of this project's original research was to quantify the benefits of frequently used strategies both individually and in combination.

The literature indicates that operational improvements (e.g., increased stop spacing, off-board fare payment) often provide the majority of the travel time or speed benefit when multiple strategies are implemented at the same time. *TCRP Synthesis 110* (Boyle 2013) noted that "successful agencies emphasized good ideas above technology. TSP and other traffic engineering actions topped the 'wish list' of responding agencies, but most of the successful actions could be implemented without new or added technology" (or infrastructure).

This project found similar results, in that bus operations strategies were often found to produce similar or better benefits for buses than strategies focused on infrastructure or technology. The project's simulation study found that relocating a bus stop from the near side to a far side produced similar delay savings for buses as implementing TSP. The combination of TSP and stop relocation to the far side produced bus delay savings that were approximately additive (i.e., the benefit of the two strategies combined was approximately the same as the sum of the benefits from the two strategies if implemented individually). An analysis of AVL data from a 5-mile portion of a BRT line in Seattle, where different strategies were implemented separately (business access and transit lanes, traffic-responsive signal timing, and off-board fare payment and headway changes) found that only the operational changes resulted in shorter bus travel times through the corridor.

This project also confirmed through simulation that the benefits of TSP and other strategies applied at spot locations, while appearing to be beneficial on an individual intersection basis, may in some cases not produce significant bus time savings when evaluated on a corridor basis. One potential cause for this result is that the next downstream signal can negate the delay benefit from an upstream signal. 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. This project developed an analytical method for estimating the likelihood that a bus will be able to make the green light at a downstream signal, thus preserving the delay benefit provided by a strategy implemented upstream, building on work by St. Jacques and Levinson (1997).

This is not to say that signal timing, regulatory, and infrastructure strategies have no role to play. On the contrary, many strategies of these types were found that provide meaningful transit benefits. Operational strategies are well-suited to combining with other strategies to produce a greater benefit than could be achieved by either in isolation. In addition, operational strategies provide a low-cost, readily implementable starting point for improving bus speeds and reliability in jurisdictions where transit service is not prioritized.

Innovative Strategies

This project reviewed international best practice for strategies that were identified through the literature review or agency interviews as (1) being regularly used internationally but not in the U.S., (2) lacking U.S. guidance on their use, or both. Implementation guidance was developed for the following strategies:

- *Bus-only signal phases* that allow buses to make unconventional turning movements at intersections (e.g., left turns from the right lane).
- *Pre-signals* that can be used to (1) create a virtual bus lane on an intersection approach where a physical bus lane is infeasible, (2) to help buses weave across

traffic lanes from a bus lane to enter a left-turn lane, and (3) to help buses merge into traffic at the point a bus lane ends.

- *Bus boarding islands,* which allow bus stops to be located within the roadway and help support strategies such as queue jumps at intersections with channelized right-turn lanes and left-side bus lanes.
- *Reversible bus lanes,* that switch direction by time of day or on an as-needed basis as buses arrive.
- *Phase reservice,* in which a minor movement (e.g., a protected left turn or a minor street approach) is served twice within the same cycle, which can reduce delay for buses making those movements.

Methods for helping buses make left turns to or from busy streets were also investigated. The MUTCD does not currently provide a signal warrant to install traffic signals solely to serve bus movements (unless the bus volumes are sufficiently high to meet one of the MUTCD's volume-based warrants). Two "shadowing" methods were investigated for their potential to meet the transit need while working within the MUTCD framework. The first method considered would have buses trigger a pedestrian hybrid beacon, thereby creating a gap in traffic that could be used for bus left turns. This was determined to be infeasible, as the MUTCD does not allow such beacons to be used at intersections (only at mid-block locations) and because it could reduce motorist respect for the device if motorists had to stop, but no pedestrians were present. The second method considered would call a left-turn phase at a downstream intersection to create a gap. This was determined to be feasible, but a much less satisfactory option than providing a signal at the intersection where the transit need existed.

Canadian guidelines (Corby et al. 2013) recommend the use of a "signal installed specifically for transit" in situations where buses have difficulty making left turns, but note that this treatment is not allowed everywhere in Canada. A proposed new MUTCD chapter would allow traffic signal control as an option to serve busway movements where a busway crosses another roadway at grade (NCUTCD 2015). The term "busway" was not explicitly defined in the proposed chapter at the time of writing, but if it is understood to mean any bus-only lane or off-street facility used exclusively by buses, then this proposed chapter would allow the installation of a traffic signal to serve bus movements from bus-only lanes. This would be a more straightforward way to address the transit need than a shadowing approach.

Finally, streets used by transit vehicles frequently also make desirable corridors for bicycle traffic, as 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 project reviewed U.S. and international best practice on managing bus and bicycle interactions at and between stops and developed guidance on potential solutions for accommodating both bicycles and buses, to the benefit of both modes. This guidance appears in the Guidebook as Appendix C.

SUGGESTED ACTIONS AND FUTURE RESEARCH

Actions

A review of the roadway design manuals from 16 state DOTs found that, in most cases, transit was not addressed at all within the design manuals, or only addressed to the extent of providing design guidance for bus pullouts (most common), bus stops, and park-and-ride lots. Only two states had a chapter on transit facilities within their manuals. A larger number of states had a chapter on pedestrian and bicycle facilities, and curb extensions were sometimes discussed in the context of a being a pedestrian treatment. This review suggests that an opportunity exists for state transit associations to partner with state DOTs to develop such guidance, drawing from both the AASHTO transit design guide and this project's Guidebook. Having such guidance in state design manuals would help facilitate future projects proposed on state highways, as well as projects in local jurisdictions that have adopted the state manual by reference. In addition, an update of the AASHTO transit design guide is recommended that would consider this project's recommended changes to the guide, changes related to transit preferential roadway strategies in the next edition of the MUTCD, and (potentially) guidance being developed by NACTO as part of a forthcoming urban design guide for transit.

More before-and-after studies on the outcomes of transit-supportive roadway strategy projects are needed to expand the knowledge base about these strategies, to help apply the lessons learned in one community for the benefit of the transit industry as a whole. This project found that these studies were often not performed due to staff or financial resource constraints. Transit agencies facing these constraints might consider partnering with local universities, as these make interesting real-world projects for transportation students, with opportunities for students to present and share the findings.

Future Research

Although this project advanced the state of knowledge regarding conditions under which the benefits of transit-supportive roadway strategies are lost at a downstream signal, more work can be done in this area to better quantify the situations that lead to no or negligible benefits, as well as the situations that produce very good benefits.

Very few bicycle facilities have been constructed in the U.S. that have been specifically designed to manage bus interactions with bicycles. Although this project has developed guidance in this area on the basis of U.S. and international best practice, an unknown at this point is how bicyclists behave with different types of bus and bicycle lane configurations, and what the relative safety and operations outcomes are for both buses and bicycles with different configurations. In addition, the impact (if any) on bus speeds of "Green Wave" signal progression provided for bicycles has not been studies. However, it has been speculated that—at least in central city environments where both buses and bicyclists travel at similar average speeds—that both modes could benefit.

If the proposed Busway Grade Crossings chapter is not incorporated into the next edition of the MUTCD, or if the language is changed to clarify that it only applies to longer-distance busways and not short bus-only lanes, then additional research is recommended to identify the conditions under which traffic signals specifically for buses would be appropriate to install, and to develop draft MUTCD language for such signals.

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Appendix A. Literature Review

INTRODUCTION

This appendix documents the literature review conducted for TCRP Project A-39. A summary of the findings from the literature review can be found in the "Literature Review Summary" section of Chapter 2. All references are listed in Chapter 6.

COMPREHENSIVE OVERVIEWS OF TRANSIT-SUPPORTIVE ROADWAY STRATEGIES

The following recent reports and documents describe a broad range of transit preferential strategies in use in the United States and internationally:

- ***TCRP Synthesis 83: Bus and Rail and Transit Preferential Treatments in Mixed Traffic.*** This synthesis (Danaher 2010) summarizes the previous literature providing guidance on when and where strategies could be considered, describes potential analysis methods for estimating the effects of specific strategies, and presents the results of a survey of transit and roadway agencies on their planning for, and use of transit preferential strategies. The synthesis identified five areas for future research, which helped develop the scope for TCRP A-39: (1) the effects of consolidating bus stops, (2) warrants for transit preferential treatments, (3) cumulative benefits of multiple applications of transit preferential treatments, (4) intermodal tradeoffs for intersection-based treatments, and (5) intergovernmental relationships in the development of transit preferential treatments.
- ***TCRP Report 165: Transit Capacity and Quality of Service Manual, 3rd Edition.*** The TCQSM (Kittelson & Associates, et al. 2013) provides sections on bus preferential strategies (e.g., projects with a significant capital component, such as bus lanes and TSP), bus operational strategies (e.g., stop consolidation, turn restrictions), and rail strategies. The TCQSM material builds on *TCRP Synthesis 83*'s discussion of infrastructure strategies, while adding discussions of operational strategies. It presents warrants and conditions for applying these strategies based on previous studies in the literature, in particular *NCHRP Report 155* (Levinson, Adams, and Hoey 1975).
- ***Guidelines for Planning and Implementation of Transit Priority Measures.*** This report (Corby et al. 2013), published by the Transportation Association of Canada, describes strategies in common use in Canada and provides guidance on when they might be applied. The guidelines avoid providing quantitative warrants on when to consider specific strategies, in favor of presenting a range of qualitative "assessment criteria" to be considered when evaluating a potential strategy in a particular location.
- ***Guide for Geometric Design of Transit Facilities on Highways and Streets.*** This guide (AASHTO 2014) is the latest in a series of modal design guides published by AASHTO intended to supplement the *Policy on Geometric Design of Highways and*

Streets with detailed, mode-specific design guidance. The Transit Guide's scope covers much more than transit preferential strategies, which are mainly addressed in Chapter 5, Guidelines for Bus Facilities on Streets and Roadways. A major contribution of the guide is providing recommended dimensions for various design elements, but the guide also provides qualitative discussions on when particular strategies may or may not be applicable. The guide generally avoids providing quantitative conditions or warrants for considering particular strategies, but does provide some quantitative guidance (e.g., "peak hour one-way bus volumes of about 40 to 75 buses will provide a bus presence without creating excessive bunches").

Earlier documents, including previous editions of the TCQSM (Kittelson & Associates, et al. 1999 and 2003), the *Highway Capacity Manual 2000* (HCM 2000), *TCRP Report 118: Bus Rapid Transit Practitioner's Guide* (Kittelson & Associates, 2007), and *TCRP Report 90: Bus Rapid Transit* (Levinson et al. 2003) have provided quantitative warrants for when selected transit preferential treatments should be considered. All of these can be traced back to *NCHRP Report 155* (Levinson, Adams, and Hoey 1975) as the original source. Although the source material 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 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 each of the general traffic lanes; however, at least in some cases, the recommended minimum bus volumes result in considerably higher person volumes in the bus lane relative to a typical urban street general traffic lane.

The TCRP A-39 literature review and agency interviews indicate that many strategies have been implemented with much lower bus volumes than suggested by the *NCHRP Report 155* warrants. The most recent guidance documents suggest considering a broad range of factors when considering transit preferential strategies, consistent with the evolution of traffic engineering practice toward context-sensitive solutions (e.g., FHWA 2014). This suggests that the local *policy environment* must be considered when evaluating transit preferential strategies, as local policies favoring alternative modes could justify strategies at lower bus or passenger volumes than would be justified based solely on roadway operational performance measures such as delay or throughput.

STATE DOT ROADWAY DESIGN MANUALS

The roadway design manuals from 16 state DOTs were reviewed, along with applicable companion documents (e.g., pedestrian and bicycle design guidelines, signal timing manuals, state MUTCD supplement) that existed in a given state. The DOTs were selected on the basis of operating transit service (Connecticut, Maryland, New Jersey), size (California, Florida, Illinois, New York, Texas), known involvement in transit projects on state highways (Minnesota, Oregon, Utah, Washington), and geographic balance (Arizona, Colorado, Massachusetts, North Carolina).

In most cases, transit was not addressed at all within the design manuals, or only addressed to the extent of providing design guidance for bus pullouts (most common), bus stops, and park-and-ride lots. Only two states—Oregon and Washington—had a chapter on transit facilities within their manuals. A larger number of states had a chapter on pedestrian and bicycle facilities, and curb extensions were sometimes discussed in the context of a being a pedestrian treatment.

The Florida DOT is a decentralized agency and both the central office and the district offices produce design guidance. This guidance typically includes a disclaimer that FDOT standards supersede guidance; however, the Florida "Greenbook" (FDOT 2011) is silent on the design of transit preferential strategies. The following FDOT documents provide guidance:

- The Districts 1 and 7 *Transit Facility Handbook* (Gannett Fleming et al. 2007) describe exclusive bus lanes, queue jumps, bus bulbs, and TSP, but provide limited or no guidance on when to apply to them.
- District 4's *Transit Facilities Guidelines* (FDOT District 4 2007) describe curb extensions and provide guidance based on *TCRP Report 65: Evaluation of Bus Bulbs* (Fitzpatrick et al. 2001).
- The guidebook *Accessing Transit: Design Handbook for Florida Bus Passenger Facilities* (Higgins and Audirac 2008) addresses exclusive bus lanes, TSP (referencing Chada and Newland 2002), queue jumps, and curb extensions.
- In recognition of the existence of multiple guidance documents, a summary document *Statewide Transit Facility Standards, Criteria, and Guidelines* (FDOT Public Transit Office 2010) was prepared that cross-references guidance to the document(s) the guidance appears in. The intent was to eventually develop a single set of statewide guidance, which would appear in an updated version of the *Accessing Transit* handbook.

Other information or guidance related to transit preferential strategies found in the reviewed state manuals included:

- **California.** Curb extensions.
- **Colorado.** Incorporating bus and bicycle lanes on a roadway and curb extensions.
- **Minnesota.** TSP.
- **Oregon.** TSP and curb extensions.
- **Texas.** Bus lanes, referring readers to *TCRP Report 26: Operational Analysis of Bus Lanes* (St. Jacques and Levinson 1997).
- **Utah.** Curb extensions.

The review of state DOT guidance suggests that transit preferential strategies are rarely addressed in DOT design standards. As a result, transit agencies wishing to install apply them on state highways will likely face both an educational effort to inform DOT decision-makers about the benefits and effects of such strategies, and a need for the DOT to develop their own guidance or standards for implementing and designing them. Both of these efforts will likely take time the first time a particular treatment is proposed.

TRANSIT AGENCY DESIGN GUIDES

A number of transit agency design guides were reviewed to identify potential guidance on transit preferential strategies; however, most did not provide any such guidance. Five that did were the following:

- **TriMet (Portland, Oregon).** Chapter 23 of TriMet's design criteria (2005) discusses bus lanes, queue jumps, exclusive freeway ramps, turning movement exemptions, special stopping privileges, priority merges, and TSP.
- **TransLink (Vancouver, Canada).** The agency's *Transit Infrastructure Design Guidelines* (2002) includes a chapter on transit priority measures. Three types of measures are identified:
    - Lane reservations for transit, including bus lanes, bus streets, queue jumps, and high-occupancy vehicle lanes;
    - Traffic control measures that give transit priority, including bus-only signals and bus-actuated signals; and
    - Legislative and regulatory measures that give transit priority, including yield-to-bus laws, prohibitions on other vehicles stopping at bus stops, exemptions from turn prohibitions, and exemptions to weight and length restrictions.
- **Movia (Copenhagen, Denmark).** Movia is the bus service provider for the Copenhagen metropolitan area, along with small urban and rural areas in the eastern third of Denmark. The agency has produced two editions of a guidebook (Trafikselskabet Movia 2011) designed for local municipality staff that describes a variety of bus preferential treatments and provides Movia's preferences for when they should be implemented. Movia recommends that bus priority measures be considered whenever new or upgraded signals, road improvements, street closings, and bus stop relocations are being planned or designed. Strategies covered in the guide include: special bus signals, pre-signals used prior to a signalized intersections to facilitate bus movement, TSP, various gate treatments to restrict access to an area to buses and other authorized vehicles, turn restriction exemptions, and part-time parking and stopping prohibitions.
- **Auckland Regional Transport Authority (New Zealand).** The agency's *Bus Stop Infrastructure Guidelines* (2009) contain recommendations and case studies regarding the placement of bus stops in areas where TSP has been implemented:
    - Provide priority measures at key congestion points to improve reliability;
    - Review bus stop locations when TSP is implemented at an adjacent intersection;

- Avoid locating a bus stop between a signal detector and the stop line at intersections where TSP has been implemented—the stop should be located before the signal detector; and
- Try to implement bus stop renovations, expansions, and other improvements as part of a corridor-wide treatment that may also include TSP measures.

- **Public Transport of Authority of Western Australia (Perth).** This agency's guide (2011) highlights a number of infrastructure- and traffic operations–related preferential strategies, including queue jumps, gate treatments, turning movement exemptions, hook turns, exclusive freeway ramps, and curb extensions. The guide also discusses a number of strategies related to traffic signal timing, including:
  - Timing signals to progress transit vehicles,
  - Repeating transit priority phases within each signal cycle,
  - Allocating greater green time to phases serving transit vehicles,
  - Reducing cycle lengths,
  - Extending green time or returning to green earlier during individual cycles to reduce delay to requesting transit vehicles, and
  - Special transit vehicle phase.

Given the number of comprehensive documents on transit preferential strategies now available (including this project's Guidebook), it may no longer be necessary for transit agencies to develop their own documents specific to transit preferential strategies, as they can now refer to one or more comprehensive documents of their choosing. However, it could be still be useful for transit agencies to identify preferred (or not preferred) transit preferential strategies, dimensions, and conditions for installation, specific to their own bus fleet and local conditions, as part of their overall design guidelines.

MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES (MUTCD)

The MUTCD (FHWA 2012) "is a compilation of national standards for all traffic control devices, including road markings, highway signs, and traffic signals." States are required to comply with the MUTCD's provisions or to adopt a state MUTCD that substantially conforms to the national manual. States can negotiate exceptions to specific aspects of the national MUTCD when developing their state manual—most of these are typically made to conform to state law or to specify particular signs that are not to be used within the state.

States can submit requests to FHWA on behalf of themselves or roadway agencies (e.g., cities, counties) within their state to allow them to experiment with new or different types of traffic control devices. If the request is approved by FHWA, the experimenting agency must evaluate performance before, during, and after the test and agree to remove the device if FHWA terminates the test or decides not to approve the device following the experiment. Word messages not included in standard signs required to convey information about special regulations may be used by roadway agencies without the need for experimentation. (An example would be an EXCEPT BUSES plaque to accompany a right-turn only sign.)

Traffic control devices provided in the MUTCD specific to transit preferential strategies include the following:

- BUS LANE and HOV plaques can supplement mandatory and optional movement lane control signs when the movement control only applies to buses or only to high-occupancy vehicles. (Sections 2B.20, 21)
- Gates can be used to prohibit the entry of traffic into a roadway segment or to enforce a required stop. Gates can rotate from a vertical to horizontal position or can swing or retract horizontally. Examples of possible uses of gates are provided (e.g., private community entrances and exits, toll plaza lanes), none with an explicit transit use; however, transit use is not specifically excluded. (Section 2B.68)
- Regulatory signs are used for preferred lanes (e.g., RIGHT LANE BUSES ONLY 6 AM – 9 AM MON – FRI). "Changeable message signs may supplement, substitute for, or be incorporated into static Preferential Lane regulatory signs where… multiple types of operational strategies… are used and varied throughout the day or week." (Section 2G.03)
- Preferential lanes adjacent to a general-purpose lane or separated by a space traversable by motor vehicles shall have word or symbol markings related to the preferential use—for example, BUS ONLY for bus lanes. If two or more uses are allowed in the lane, the word or symbol for each use shall be provided. Marking spacing is determined by engineering judgment and should consider prevailing speeds, block lengths, and distance from intersections; 80-foot spacing might be appropriate for urban streets, while 1,000-foot spacing might be appropriate for freeways. (Section 3D.01)
- Longitudinal pavement markings separating preferential lanes from general-purpose lanes are specified for various situations (e.g., barrier-separated right-hand side, contiguous left-hand side). (Section 3D.02)
- Colored pavement is only allowed for delineating flush or raised median island (yellow) or channelizing island (white). (Section 3G.01). The next edition of the MUTCD is expected to permit red pavement for public transit use (e.g., bus lanes); however, until that edition is released (or FHWA issues an Interim Approval), highway agencies must submit a written request to FHWA to use red pavement. New York City and San Francisco have been granted permission to experiment with red pavement for bus lanes.
- Traffic signals should not be installed unless, at a minimum, one or more warrants are met: eight-hour vehicular volume, four-hour vehicular volume, peak hour, pedestrian volume, school crossing, coordinated signal system, crash experience, roadway network, and intersection near a grade crossing. The coordinated signal system warrant can be used to justify a signal at a location where it would not otherwise be needed when a traffic signal would improve the platooning of vehicles;

the resulting signal spacing should be 1,000 feet or greater. (Chapter 4C) No warrant is provided for installing traffic signals specifically for facilitating bus movements. Because of the ongoing maintenance expense associated with installing a new traffic signal, many roadway agencies will only consider some of the MUTCD warrants—for example, the peak hour warrant, which warrants a signal based on conditions that occur one hour per weekday, is often not allowed.

- Traffic control signals may be allowed to respond to certain classes of vehicles, such as transit vehicles, by "altering the normal signal timing and phasing plan(s) during the approach and passage of these vehicles." The alternative plan(s) may be as simple as extending a currently displayed green interval or as complex as replacing the entire set of signal phases and timing. Light rail transit signal indications (vertical, horizontal, and diagonal bars) may be used to control buses in queue jumper lanes and bus rapid transit at signalized intersections if engineering judgment indicates that road user confusion would be reduced. (Section 4D.27)

Many existing transit preferential strategies are explicitly allowed in the MUTCD, including bus lanes, bus exemptions from turn restrictions, gates, TSP, and special transit signal indications. Red pavement for bus lanes is expected to be added in the next edition of the MUTCD. Two strategies used internationally that are not specifically addressed in the MUTCD are pre-signals (signals used to manage queues and provide gaps for buses located upstream of a signalized intersection) and bus left-turn signals in combination with pedestrian crossing signals or beacons. The latter two strategies were the topic of additional study as part of TCRP Project A-39 and are discussed further in the "Innovative Strategies" section of Chapter 4 and in Appendix A.

STRATEGY-SPECIFIC GUIDANCE

Several transit preferential strategies have been the subjects of comprehensive research projects, including bus lanes, TSP, curb extensions, roadway shoulder use by buses, and shared bus and bicycle lanes.

TCRP Report 26: Operational Analysis of Bus Lanes on Arterials (St. Jacques and Levinson 1997), and the follow-up *TCRP Research Results Digest 38: Operational Analysis of Bus Lanes on Arterials: Application and Refinement* (St. Jacques and Levinson 2000), developed analytical tools for evaluating the impact of several different bus lane types (including mixed traffic operations), passive signal priority, and bus stop spacing on bus speeds. These reports utilized the performance measure *travel time rate* (e.g., minutes per mile) to evaluate the impact of strategies.

An American Public Transportation Association (APTA) recommended practice on *Designing Bus Rapid Transit Running Ways* (APTA 2010) addresses the geometric design of BRT running way alternatives, including busways on exclusive rights-of-way, exclusive bus lanes, and mixed traffic on arterials. The document specifies typical horizontal alignment, vertical alignment, and cross-section design values for each type of BRT facility, as well as other design considerations such as pavement structure, drainage, landscaping, lighting, utilities, signage, and pavement markings.

The U.S. Department of Transportation produced *Transit Signal Priority: A Planning and Implementation Handbook* (Smith, Hemily, and Ivanovic 2005) to educate traffic engineers and transit planners on TSP and provide technical guidance on implementing a successful TSP project. The handbook advocates a systems engineering approach, encourages collaboration with stakeholders from day one, and employs eight case studies to demonstrate its guidance. It also reports corridor travel time savings that have been achieved due to TSP (ranging from 9 to 16% in the studied cities), as well as reductions in travel time variability. Finally, the handbook provides technical information on signal control equipment and software, detection systems, and communication systems, as well as an overview how simulation and signal timing optimization tools can be used to assess the impact of TSP.

The *Signal Timing Manual,* 2nd Edition (Urbanik et al. 2015) is "a comprehensive guide for engineers and technicians about signal timing principles, practices, and procedures," including sections on signal timing fundamentals, basic signal systems, and advanced systems and applications. It encourages consideration of all of a signal system's users, including pedestrians, bicyclists, and transit passengers. TSP is discussed in Chapter 10, Traffic Signal Preferential Treatment, along with signal priority for emergency vehicles and trucks, and signal pre-emption associated with nearby railroad grade crossings. The chapter first discusses generally how priority is granted in response to one or more requests and then discusses specifics for different types of requesting vehicles. The transit material includes a discussion of potential conditions that might be used to determine whether or not or grant signal priority to a transit vehicle (e.g., early or late relative to the schedule, in or out of service, passenger load, relative priority of specific routes or specific directions of routes).

TCRP Report 65: Evaluation of Bus Bulbs (Fitzpatrick et al. 2001) reports on an evaluation of curb extensions (bus bulbs) on transit operations, vehicular traffic, and nearby pedestrian movements. The conditions used by the studied cities to determine when to install curb extensions included transit considerations (e.g., reducing bus delays re-entering traffic, providing space for shelters and other amenities), pedestrian considerations (e.g., reducing pedestrian crossing distances, improving sidewalk flow), business considerations (e.g., providing a defined space for waiting transit passengers away from storefronts), and traffic considerations (e.g., automobile delay, traffic calming). The report found that curb extensions are appropriate in areas with high-density developments and in which 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. Furthermore, the average flow rate of pedestrians traveling along sidewalks adjacent to bus stops improved following construction of curb extensions.

TCRP Report 151: A Guide for Implementing Bus on Shoulder (BOS) Systems studied bus-on-shoulder operations on both freeways and arterial roadways in 14 regions in North America (Martin, Levinson, and Texas Transportation Institute 2012). The report provides guidance on the design and operation of shoulder lanes and documents time savings of 3–7 minutes per trip (generally proportional to the distance travelled) and good travel time reliability where such lanes have been implemented.

A research project sponsored by the Florida DOT (Hillsman, Hendricks, and Fiebe 2012) inventoried 27 roadways in the U.S. where shared bus and bicycle lanes were in operation, other instances in the U.S. where such lanes were being planned or had been removed, and selected international examples. These lanes are 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. The researchers found little state guidance on the design of shared bus and bicycle lanes, but some local and regional guidance, along with international examples. They also contacted FHWA for guidance on signing these lanes. Recommendations for future research that are relevant to this project included the need to study the impact of these lanes on bicycle, bus, and general traffic mobility; a crash analysis of different designs; and an evaluation of alternative bus stop treatments to safely guide bicyclists though conflict areas. This research is discussed further in Appendix B, Managing Bus and Bicycle Interactions.

Considering this strategy-specific material in combination with the comprehensive references described earlier, the TCRP A-39 researchers concluded that a strong base of standards and guidance for the geometric design (e.g., lane widths) exists for most commonly used transit preferential strategies.

INTERAGENCY PARTNERSHIP GUIDANCE

A key focus of TCRP A-39 was to identify best practices for cooperation between roadway agencies, transit agencies, and other stakeholders when planning, designing, and operating transit preferential strategies. This section summarizes the documents that were reviewed on this topic.

TCRP Legal Research Digest 42

TCRP Legal Research Digest 42: Transit Agency Intergovernmental Agreements: Common Issues and Solutions (Thomas 2012) identifies a range of transit-related issues that have been addressed in previous intergovernmental agreements (IGAs) and memoranda of understanding (MOUs). Topics include assigning operational decision-making responsibility, agency coordination obligations, service commitments and standards, provisions applicable to third parties, use of consultants, and procurement obligations. The digest also provides examples of many different types of IGAs and MOUs, including the following with relevance to TCRP A-39:

- 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 IGA between a transit agency and a city to utilize 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."
- A license issued by a city to a transit agency to use city right-of-way in connection with transit service expansion.

Shared-Use Bus Priority Lanes on City Streets

Agrawal, Goldman, and Hannaford (2012) examined the strategies needed for public agencies to coordinate and share authority over different elements of BRT systems, including design, operations, and enforcement. Their report includes case studies of the design, facility type, and enforcement, and scope of several different types of preferential strategies. Regarding inter-agency coordination, they find that responsibilities for BRT systems are typically "split among agencies responsible for street engineering, transit services, and policing, as well as across multiple levels of city government," although several metropolitan areas have proposed integrating these responsibilities into urban transportation agencies. Bus lane enforcement is limited by the legal and political systems governing each facility, but many agencies have prevailed by either using contracts between police and transportation agencies to create relationships for better enforcement or by designing BRT facilities that are easier to enforce.

United Kingdom Guidance

A guide by the U.K. Department for Transport (2011) emphasizes the need for constructive collaboration as a means to improve bus punctuality and reliability. The guide describes a partnership approach that includes clear roles and responsibilities for each party involved, and highlights several best practices in the form of case studies. The guide calls for more data sharing, timely constructive dialog, and "a shared commitment to achieving a high standard of service punctuality to benefit the passenger." The guide introduces a model for partnering and provides a detailed description of each model component. A second guide from the U.K. (UK Department for Transport, Local Government and the Regions 1997) describes the stakeholders involved in bus preferential strategies, including bus operators, traffic commissioners, traffic authorities, local authorities, passenger transportation executives, law enforcement agencies, user groups, and environmental agencies. The report's appendix summarizes these stakeholders' roles and responsibilities in developing and regulating transit services and infrastructure and states that "close co-operation between these agencies is essential if such measures are to operate satisfactorily." While agency responsibilities in the U.S. may differ from the U.K., it is still useful to review the full range of stakeholder types that may need to be considered when implementing transit preferential strategies.

TCRP Synthesis 110

TCRP Synthesis 110: Commonsense Approaches for Improving Transit Bus Speeds (Boyle 2013) presented the results of survey responses from 59 transit agencies in the U.S. and Canada on strategies they have used to improve bus speeds. The strategies were categorized by the following: schedule adjustments (e.g., reducing hold time at timepoints), route adjustments, stop-related actions, vehicle-related actions, external policy changes (i.e., anything requiring the cooperation of another agency), internal policy changes (e.g., pre-paid fare payment), and other actions. Although a number of strategies had been used by the majority of survey respondents, in general no more than one or two transit agencies had quantified the impact of any given strategy.

The four most common reasons that agencies did not implement desired strategies were:

- Rider opposition (e.g., requiring a longer walk to a bus stop),
- Lack of roadway agency cooperation (e.g., allowing bus lanes or providing TSP),
- Community opposition (e.g., removing on-street parking, relocating a stop), and
- Lack of funding.

Findings related to establishing partnerships with stakeholders included:

- Outreach should include an education element, as stakeholders may focus on the perceived disbenefits of the strategy to them and may not be aware of the benefits a strategy will provide.
- Establishing a good working relationship with roadway agencies is essential when considering strategies (e.g., bus lanes, TSP) that impact roadway infrastructure. At the same time, the synthesis identified a number of successful transit operations strategies that a transit agency can undertake themselves.
- Quantifying the outcomes of an implemented strategy can help build the case for future, possibly more challenging, implementations.
- High-level management support is essential, but it is also useful to involve all departments within the transit agency.
- Keep focused on the long-term objective and recognize that there will be challenges and opposition to overcome in the short term.

Recommendations for future research that were relevant to TCRP A-39 were:

- Analysis of the effectiveness of individual strategies at the stop and route segment levels.

- Ways to develop closer working relationships between transit and roadway agencies.
- Addressing specific roadway agency concerns that certain types of treatments were not endorsed by national manuals such as the MUTCD.

CASE STUDIES

This section summarizes papers and reports that quantify the outcomes of specific applications of transit preferential strategies not included in the more comprehensive reports discussed earlier.

City-Specific Studies

TriMet and the City of Portland, Oregon implemented a package of transit preferential strategies—TSP, stop consolidation, curb extensions, and bus pullout removal—to twelve "streamlined" routes. These routes also received the first buses in the fleet equipped with stop-announcement features and were the first routes where new bus stop signs were deployed. Comparing route performance in 2005 to 2000 (Koonce et al. 2006), the streamlined routes were 0.8 minutes faster, while nine similar non-streamlined routes were 1.3 minutes slower. On-time performance degraded 3 percentage points on the streamlined routes, compared to 6 points on the non-streamlined routes. Although no route saved enough time to allow a bus to be saved, the streamlining actions postponed the need to add a bus to a route by 8 years on average.

Albright and Figiliozzi (2012) studied the effect of TSP performance on a congested arterial corridor in Portland, Oregon, focusing on conditional transit priority, where priority is granted only to late-running buses. The paper concluded that TSP seems to be more effective in bus routes with severe lateness and at intersections with lower volumes and without significant queuing. Additionally, the research showed that TSP effectiveness (evident at the stop and intersection level) can be "hidden or evened out when analyzing effectiveness at a route level." It is therefore important to evaluate TSP on both a route level and intersection level.

Rephlo and Haas (2006) describe a TSP implementation along a 9.8-mile segment of an arterial in Sacramento, California that experiences traffic volumes exceeding 100,000 vehicles per day in some sections. Bus travel time decreased by 4% along the corridor and bus reliability improved during one-third of the time periods studied. Mobility increased along the corridor, but decreased for cross-street movements, although the authors advise interpreting those results with caution due to data collection issues.

Narrigan et al. (2007) studied a TSP implementation on one of the busiest bus routes in Springfield, Massachusetts. Other changes implemented at the same time were a more efficient routing and a change to limited-stop operation. The combination of these three reduced travel times from 45 minutes to 30 minutes, but the paper did not isolate the proportion of the time savings attributable to TSP.

Strategy-Specific Studies

An International Association of Public Transport (UITP) working group reviewed TSP in 29 cities around the world (Gardner et al. 2009). Each of the cities surveyed gave a positive review of their system. A wide range of benefits were reported; for example, travel time savings of between 2 and 24% were reported. The report noted that "benefits are often affected by the policy adopted rather than the capability of the system," and gives as an example London's policy constraint of producing minimal impact on other traffic. (Other literature also notes that the quality or lack thereof of the original signal timing also plays a role—TSP will have a smaller effect in situations where signal timing is already optimized.)

A Federal Transit Administration (FTA) report (Li et al. 2008) on implementing TSP provides cost information (as of 2008) for various types of TSP systems. It also reports on the results of implementing TSP in two corridors in the San Francisco Bay Area:

- TSP was implemented at 21 intersections along a corridor in the San Jose area. The benefit of TSP was highest at intersections where buses were stopped for 30% of more of the traffic signal cycle length and decreased as the percentage of stopped time decreased. On-time performance improved by 4 to 6 percentage points and average schedule deviation at the route end decreased by 1 to 2 minutes. Impacts to major and minor street delay were statistically or practically insignificant when volume-to-saturation (v/s) ratios (the proportion of green time required to serve vehicular demand) were 0.7 or less. At higher v/s ratios, major street delay was reduced 9–27%, while minor street delay increased an average of 8%.
- TSP was implemented at five intersections in San Mateo County. Bus travel times were reduced by 32–51 seconds through the section, corresponding to 2.4–3.4 mph increases in average speeds. Average major street delay at each intersection was reduced by 0.2–3.5 seconds, while minor street delay increases were statistically insignificant at four intersections and increased by 1.5 seconds on average at the fifth intersection.

Appendix B. Agency Interviews

INTRODUCTION

This appendix documents the agency interviews conducted for TCRP Project A-39. A summary of the findings from the interviews can be found in the "Agency Interview Summary" section of Chapter 2. All references are listed in Chapter 6.

COLUMBUS, OHIO

The Central Ohio Transit Authority (COTA) was in the early stages of planning a BRT line along Cleveland Avenue in Columbus at the time of the interview, with 60% design plans scheduled to be completed by September 2014 and service planned to start in September 2017. The project extends through two cities, one township, and one village. At the time of the interview, their stakeholders consisted of Columbus' director of public works and city council transportation committee chair, Westerville's city manager and planning director, Minerva Park's village mayor, Clinton township's mayor, three county commissioners, church leaders who are defacto neighborhood leaders, the (elected) Franklin County engineer, and representatives from the Ohio DOT, the local MPO, and a special improvement district.

Most of the current stakeholders have been involved from day 1 of the project. COTA conducted public meetings and held one-on-one interviews with the stakeholders. They focused first on public officials to build support and buy-in for the project, and then started including the people who would actually be doing the work during the planning and design phases. When the project first kicked off, all of the legal teams from each impacted agency were brought together, along with higher public officials and decision-makers who would be involved in the project. During the alternatives evaluation phase, the stakeholder group at that time (city/county planners, neighborhood leaders, business association leaders) and the technical group each had separate meetings. COTA added a CEO advisory group of high-level elected officials to keep them updated on the progress of the project.

They currently have a non-binding MOU with the cities and the state for the project development phase that states the project purpose. At a later stage in the project, COTA will develop an interagency local agreement that will specify who does what and who will fund what. One township is not yet on board with the project, due to the need to acquire land for a transit station. COTA is still working on getting that township's buy-in on the project.

To help build support for the project, early in the process COTA took the stakeholders on a bus tour of the line to show them the operational issues they were experiencing and to discuss how BRT would operate. As part of the project, COTA will be adding fiberoptic lines, repaving curb lines, and adding sidewalk connections, which the City of Columbus appreciates, since this work also benefits the city.

One of the challenges COTA has experienced has been issues with right-of-way allocation. In particular, there have been many discussions with the City of Columbus about getting a dedicated lane for BRT within the limited right-of-way, while not impacting the dedicated bike lane. These discussions have resulted in the plans incorporating both a dedicated lane for BRT and keeping the bicycle lane, even though left-turn lanes will need to be removed to accommodate the transit and bicycle lanes. COTA intends to resolve this design issue when they begin their project development, environmental clearance, and preliminary engineering stage, likely in 2016. Another early challenge was helping the stakeholders understand the idea of BRT operating in mixed traffic, since most were familiar with Cleveland's BRT line, which operates in an exclusive right-of-way.

COTA's suggestions to others pursuing similar projects include the following:

- Incorporate the bicycle community from the start of the project.
- Keep people informed by communicating clearly and often.
- Listen to stakeholder preferences for meeting times. For example, the business community in Columbus preferred meetings first thing in the morning as opposed to evening meetings. COTA had much better meeting participation when they were scheduled according to stakeholder preferences.
- Another approach to stakeholder involvement that worked well 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 was received from generic letters or emails.

DALLAS, TEXAS

Dallas Area Rapid Transit (DART) initiated a project to incorporate TSP at signalized intersections along the downtown Dallas transit mall as part of their light rail system expansion. The expansion involved adding the Green Line route to the existing Red and Blue lines, resulting in train headways decreasing to 2.5 minutes in each direction. To serve the reduced train headways while maintaining progressive traffic movement and serving pedestrian activity downtown, DART realized that TSP would be a necessary element.

Since this project involved the expansion of existing light rail and the introduction of TSP to the City of Dallas, the only major stakeholders involved were DART and the City of Dallas. DART also reached out to City Council members to educate them on the project and build consensus.

To gain support from the City of Dallas, which owned and operated the traffic signal system, DART arranged, through FHWA's Peer-to-Peer Program, visits to Los Angeles and Salt Lake City to learn more about how those agencies have implemented TSP. The tour was funded by FHWA and provided an opportunity for City of Dallas engineers to meet with other signal system operators and to learn how implementing TSP impacted their systems. The tour was a very beneficial learning experience for both DART and City of Dallas attendees.

One of the hurdles to overcome was a perception that the combination of increased light rail traffic and TSP was going to cause significant traffic problems along the transit mall and throughout downtown Dallas. DART staff hired a consultant to conduct a traffic analysis of the downtown traffic signal system. This analysis incorporated both the existing transit mall operations as well as the proposed operations following the light rail expansion and TSP implementation. This work was performed to verify that the transit mall could handle the additional light rail traffic without negatively impacting vehicular and pedestrian operations. Level of service and corridor travel times were compared for the existing condition and with transit priority in place.

DART's takeaways from this project include the following:

- Involve stakeholders early in the process and educate them about the project's needs. In this case, DART involved their stakeholders early in the decision-making and design process.
- DART funded consultant services to provide the City of Dallas with the expertise to design and implement the necessary improvements to their traffic signal system to get TSP operation functional.
- Try to put yourself in each of the stakeholders' positions. By gaining an understanding of their concerns and challenges, you will achieve better, mutually beneficial results. This approach has been followed beyond the TSP project and both agencies have seen improved cooperation on a daily basis in addressing the challenges that have arisen since the project was completed.

EUGENE, OREGON

Lane Transit District (LTD) has implemented two BRT lines since planning first began in 2000, when BRT was a relatively new concept nationally. Much of the first line ran along a state highway. Stakeholders in the projects included the City of Eugene's city traffic engineer and planning staff, Oregon DOT's regional engineer and local staff, Lane County's transportation planning manager, and LTD staff at all staff levels. In addition, the local Chamber of Commerce provided input from local businesses and looked out for their interests. All stakeholders were invited and involved from the beginning, however, the city and state were most active at the onset, because they owned and operated the majority of the infrastructure that would be used by the initial BRT line.

LTD formed a technical advisory committee for the project. Its primary purpose early on was getting the city and the DOT on board with BRT and TSP, in part by showing how it was successful in other cities. The city traffic engineer had an established relationship with the ODOT regional engineer and could explain in technical terms how the TSP system would work. This interaction was very helpful in getting the ODOT engineer on board with the project.

Not all DOT staff levels were involved with the project early on and had to get up to speed with the project later on. Once these staff became involved and understood the project, things progressed more smoothly. The FTA was not involved early on in the first BRT project, which resulted in some slowdowns. The second project ran more smoothly, with FTA already on board and open lines of communication established from the first project.

LTD held public meetings to inform local groups about the project and to solicit input. Concept drawings developed by landscape architects that depicted different elements of the proposed BRT line were used to help convey the BRT concept to the public. The project had already progressed through the regional planning process, so many stakeholders were already aware it was coming.

One hurdle that was encountered was the Eugene tree ordinance, which required a vote of city residents before any tree more than 50 years old could be cut down. A portion of the first BRT corridor was planned to run in the street median, but the trees in the median were slightly more than 50 years old. As a result, the planned two-lane busway had to be changed to a single-lane, bi-directional facility to avoid the trees. However, this has created operational issues with buses waiting for the opposing direction to clear before they can proceed, and LTD hopes to be able to add a second BRT lane at the time the city widens the roadway.

Another hurdle encountered was that the City's planning department didn't want the route on a straight line between two stations, because that alignment would have required eliminating on-street parking, which was a politically hot topic at the time. However, the project designers were able to get one direction of BRT on the street, and it turned out later to be operationally better to separate the two directions.

LTD would recommend to others to build strong relationships with stakeholders, as you will be working together for many years. Bring stakeholders on board as early as possible. Working with neighborhood associations to help them understand the process and project is beneficial. Neighbors that are supportive will want to work with you to minimize any negative opposition. LTD started visiting small businesses along the corridor, since the business owners didn't have time to attend the meetings. They devoted three staff members to walk the corridor and talk with each business owner on the route, which developed good relationships.

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 (FDOT). Thus, implementing transit-supportive roadway treatments in Florida typically requires local transit agencies and FDOT 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. JTA had discussed bus rapid transit and bus lanes with FDOT, but didn't have any construction dollars to bring to the table. However, when FDOT was planning a resurfacing project for Blanding Boulevard, they saw an opportunity to restripe the existing, little-used parking lane as a bus lane, and began working with JTA to make it happen. JTA developed typical bus lane sections and led preliminary design and public involvement efforts (all with consultant help). FDOT'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 signage, and advocated for the project at the FDOT district level.

JTA worked with stakeholders from all staff levels from Jacksonville's Public Works Department, Downtown Vision Inc., Jacksonville Economic Development, and FDOT. They also met with downtown business representatives and residents who attended public meetings on the project. The majority of the stakeholder participation took place during project construction. Project-specific stakeholder meetings were not held; instead, the project was addressed as part of regularly scheduled agency meetings that were already taking place. JTA feels that the agency stakeholder involvement occurred appropriately for the project, however, public involvement needed to take place much earlier. For example, there were condos along the project corridor that were empty during the recession, but were then purchased and occupied while the project design effort was underway. JTA staff needed to understand the Downtown Vision and its role in promoting downtown activity. Stakeholders needed to understand technical terms and this issue was addressed over the course of numerous meetings. Stakeholders were receptive to JTA's efforts to explain technical terms.

One of the issues that came up during the project was the loss of parking. Although the parking lane was not well-used, those who did use it were initially opposed to losing it—vocal users included a flea market (truck parking on Saturdays), a school (student drop-offs on weekdays), and some businesses. JTA used its contractor to develop a new circulation plan for the school (off the arterial) that the school ultimately preferred. Although the others who lost parking called up City Commission members, FDOT support went a long way, and the opposition eventually died down.

Another project challenge was how to sign the lane, as this would be the first of its kind in Florida, and this was something that was not identified as an issue right away. Right turns would be allowed from the bus lane at driveways and intersections. JTA wanted signage that would work well for its drivers and overall bus operations, while FDOT wanted to make sure the lane would operate safely. FDOT's Traffic Operations section developed the signage. The sheriff's office was unfamiliar with bus lanes and said they would not enforce the lanes. 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 lane was restriped, a public awareness campaign was conducted on how to use the bus lane. 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). 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.

Although the lane is relatively narrow (10.5 feet, plus a 1-foot gutter), it has worked well. JTA was more worried in advance about how the lane would operate than FDOT was. JTA surveyed its operators one month and seven months after opening about motorists yielding the right-of-way, bus lane violations, intersection safety, ability to make up lost time, and tenor of passenger comments, and all results were positive. Most drivers (82%) said “no problem” with continuing the effort. Although the number of buses using the lane is relatively low (JTA buses on 40-minute headways, plus school buses, paratransit vehicles, and county transit buses), there have been few comments about converting the lane into a travel lane. However, JTA feels that if a travel lane had been taken, the “empty lane” issue would have been more of a problem.

No before-and-after study has been conducted; both JTA and FDOT expected that there would be travel time and delay benefits, but did not quantify them or set targets. No accidents had occurred at the time of the interview. The project was a relatively “easy sell” to implement and has resulted in a dedicated lane on the ground that should help build support for future, more complex lanes. The City Commission is now favorable toward more projects.

The project is an outcome of the amount of inter-jurisdictional cooperation that already existed. FDOT is a funding partner in BRT projects and FDOT has a staff person focused on transit grants and BRT. FDOT is proactive in regularly meeting with local government engineering and transit staff to coordinate activities and to identify needs and opportunities. The MPO is also a partner in regional planning. The project did not change FDOT’s relationship with JTA, but it has helped FDOT staff recognize ways to improve other modes’ operation without negatively impacting automobile operations.

LOS ANGELES, CALIFORNIA

Los Angeles has implemented two types of on-roadway BRT services: (1) the Metro Rapid on-street BRT lines and (2) the Silver Line, a freeway-based line that runs in managed lanes in freeway medians. A third type of service, the Orange Line, operates in an exclusive right-of-way; however, as off-street transitways are not a focus of TCRP A-39, it was not discussed in the interview.

Metro Rapid

The need for the Metro Rapid program was identified by the Los Angeles County Metropolitan Transportation Authority (Metro) in the late 1990s through a realization that average bus speeds had declined by about 10% from the 1980s to the 1990s. In addition, a study by the City of Los Angeles DOT (LADOT) found that buses were stopped about 50% of the time they were in service—at traffic lights, in traffic congestion, or to serve passengers. Metro obtained funds from the FTA’s BRT demonstration program to implement the first two lines. The Metro Rapid program has focused on quick implementations, speeding up service by making fewer stops and implementing transit signal priority, rather than obtaining right-of-way or taking lanes from general traffic.

The Rapid lines were among the first wave of primarily on-street BRT service in the U.S. and therefore only had international experience to draw from. Long-range planners from the county planning department were involved in developing the concept and program. Consultants were used to help plan the operation and implementation of the initial lines. The LADOT installed the TSP system within the City of Los Angeles. Various local jurisdictions were involved with installing bus stops and shelters. The initial lines achieved a 25% speed improvement compared to the previous local service, attributed to one-third stop consolidation, one-third TSP, and one-third to more-balanced passenger loads through headway-based scheduling and headway management. They also attracted new discretionary riders.

As the Rapid program has expanded outside the City of Los Angeles, Metro has had to implement TSP in a different way. The City system uses a low-cost bus-mounted "hockey puck" transponder to communicate with traffic signal controllers through existing in-street loop detectors and all Rapid buses are equipped with these transponders. However, to initiate traffic signal priority on county roadways outside the City of Los Angeles, an onboard computer has to communicate wirelessly with the signal controllers, which is a more-expensive solution. Rapid buses with the necessary equipment for county TSP priority are assigned to specific bus divisions.

Newer Rapid lines typically do not achieve a 25% speed improvement, with 20% or better now being targeted. Lines that don't achieve at least a 20% improvement become candidates for being discontinued. Rapid buses will always have a faster in-vehicle time than local buses, but wait time is also a consideration in the overall trip time; so frequency is also an important factor in attracting passengers to the Rapid lines.

LACMTA initiates their projects by bringing together all agencies that are or may be involved or impacted by a project to discuss project goals and individual agency impacts, to build consensus, and to identify funding sources. For both the Metro Rapid and Silver Line projects, one of their successes was identifying and establishing a comprehensive list of stakeholders at the very beginning of the projects and getting participation from these stakeholders from day one. Their stakeholders included transit agencies in the region, city representatives from all agencies that may be impacted, and various community and business organizations. Over the course of the two projects, they held over 100 different meetings for informational presentations, marketing, soliciting input, and building consensus.

Lessons learned from the Rapid program included the following relevant to TCRP A-39:

- *Bus stops.* The initial idea was to have separate networks, so local buses were provided with near-side stops and Rapid buses were provided with far-side stops. In practice, persons took the first bus that came along if they were going to a major destination, which meant running across intersections to the other side, something they called the "Rapid shuffle." As a result, all bus stops are now located far-side. In addition, passenger trip lengths are considered when planning and evaluating Rapid lines. The intent is that Rapid buses serve longer-distance trips and local buses serve shorter trips, but if trip distances end up being the same, the Rapid service may be discontinued, with the service reassigned to produce shorter headways on the local route.

- *Downtown bus stops.* Downtown stops are a special case, as many bus routes converge on downtown, including those from municipal (non-Metro) operators. Here, they try to evenly space stops and to identify and group routes that go together or to similar destinations. In downtown, Rapid stops are consolidated with local stops—this is better from a user perspective, but it does dilute the BRT brand.

Silver Line

The Silver Line is an evolution of earlier freeway-based express bus service on the Harbor (I-110) and San Bernardino (I-10) freeways. From the south, local bus lines would converge on the Harbor Gateway Transit Center in San Pedro, run on managed lanes on the freeway (the Harbor Transitway), making station stops along the way, and continue on surface streets to the north end of downtown. From the east, lines would converge on the El Monte Transit Center, run on the El Monte Busway to downtown, making station stops along the way, and continue on surface streets to the south end of downtown.

The Silver Line, which began service in late 2009, split the local service from the freeway service and tied the freeway portions together as one continuous route. Downtown-bound passengers boarding local service (about 13% of total ridership) must transfer to the Silver Line at the transfer centers. Silver Line buses have transponders that allow them to activate TSP in downtown Los Angeles, and a new bus lane has been constructed on Figueroa Street in downtown by converting right-turn lanes to bus-only lanes. The Silver Line upgrades were performed in conjunction with changes to the managed lanes to implement tolling, as the previous carpool lanes had reached capacity. The California DOT (Caltrans) recognized that additional bus service would need to be part of the solution to accommodate some of the displaced carpoolers. In the end, 70% of the congestion management grant funding for the express lane improvements went to improving transit, including new buses, rebuilding the transit centers and transitway stations, and implementing the Figueroa bus lane.

Because the Silver Line converted existing lines and created a new service, more outreach was conducted than had been done for the Rapid services. The 13% of riders that boarded local buses and continued onto the freeway segments were surveyed; the majority of these riders didn't care which service option was used or thought that the proposed Silver Line was a good idea.

LACMTA's project approach included developing a Project Charter at the onset. This document was used to ensure that all stakeholders understood from the start what the project involved and what was required from each stakeholder. The Project Charter also helped provides consistency when there was turnover in a stakeholder representative.

For example, the Project Charter for the Silver Line outlined that the project purpose was to implement managed lanes on the freeway and discussed the various agencies' roles and responsibilities. The charter included details about existing managed lane implementations that could be applied or adapted to the Silver Line project. When one of the department heads from the state DOT—a supporter of the project—left the agency, having the charter helped the person's replacement get involved in the project, as the new person's role was clearly identified in the charter.

One of the keys to their success was having a strong project manager who could work with a variety of interests and personality types to stay on track with the project's goals and keep all stakeholders engaged and focused. One of the challenges faced in working with the stakeholders was keeping topics boiled down to terms that were easy for everyone to understand.

LACMTA also made presentations to the South Bay and Valley regional boards (governance councils) during the planning and implementation process. When the new service started, Metro placed customer ambassadors at the stops to help them navigate. There were no significant issues with implementation.

Transportation agencies in Los Angeles recognize that the region cannot build its way out of congestion and therefore leverage all services and prioritize what works. Metro and LADOT have had a long-standing good relationship and the Silver Line has established a closer relationship with Caltrans. Higher-capacity transportation services are being prioritized. At the same time, budget constraints limit how much can be done.

MALMÖ, SWEDEN

Malmö, with a population of just over 300,000, is Sweden's third-largest city. It is located in southwestern Sweden, along the Öresund strait separating Sweden from Denmark. It has a metro area population of approximately 650,000, while the combined Copenhagen–Malmö region has a population over 2.3 million, making it the largest population center in Scandinavia. The opening of the Öresund bridge and 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, non-motorized 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 (EPOMM 2013).

In 2003, Malmö initiated a program to improve cooperation with Skånetrafiken, the transit service provider (local bus, regional bus, commuter rail, 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, including 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 (both 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 as needed from the appropriate departments and organizations:

- *Service quality,* managing quality issues relating 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 interview was the Malmö Express BRT line. (The line opened in June 2014). The line is operated with bi-articulated, 78-foot 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-minute 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 mostly center bus lanes were added in anticipation of the future tram line, with stations in the center of the street in those sections.

The concept for one station that was presented during the interview would place the platforms one block away from a signalized intersection. A signalized crosswalk would be created at the station and the crosswalk signal would provide a queue jump function for buses and trams headed toward the signalized intersection. The transit lane was to be placed to the right of the left-turn lane at the signalized intersection, which avoided the need for a special transit signal phase (left turns are generally permissive [i.e., without a left-turn arrow], except at the largest intersections). Although the transit lane crossed the entrance to the left-turn lane, the upstream queue jump would allow transit vehicles to cross the weaving area without conflict from automobiles.

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 EU air-quality requirements: if the nitrogen oxide levels from motor vehicles sitting in queues at intersections is 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 3–4 minutes of delay per bus during the a.m. peak. Bus lanes are generally installed by taking a traffic lane, but city policy is to prioritize non-automobile modes and, in many cases, the capacity is not needed between intersections. (This is not to say that there hasn't been opposition to such changes; the transitional Malmö Express service is seen as a way to address lane-conversion issues up front, smoothing the way for the eventual transition to tram service.) On occasion, short-term (15-minute) 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.

MINNEAPOLIS, MINNESOTA

Team Transit is a program that the Minnesota DOT (MnDOT) established in the late 1980s. MnDOT commissioners and deputy commissioners got together with Metro Transit to identify ways to make better use of transit on freeways, to help alleviate congestion without spending to widen freeways. Staff at lower levels in both organizations were empowered to develop solutions, while the highest levels addressed the administrative issues. Ramp meter bypasses for buses had already been implemented in some areas, which led to more projects. One ramp meter bypass project would have required rebuilding a section of freeway to meet side clearance standards; it was decided to build it anyway without reconstruction and nothing bad happened. In order to create advantages for buses, long-existing roadway standards needed to be violated. MnDOT had to decide whether standards would prevail, or whether it would be innovative. FHWA stepped in eventually, but MnDOT ended up creating alternative standards that FHWA could accept.

The bus-on-shoulder (BOS) concept had been thought of for some time, and had been implemented on divided arterial highways with signals, but MnDOT worried that it wouldn't work on freeways due to ramp conflicts. However, when flooding closed several river crossings in 1991, creating serious traffic problems, the governor asked for something to be done. MnDOT started planning on a Thursday and had BOS operational on a freeway the following Monday. It worked fine, so the concept was expanded to other freeways starting in 1993. However, the concept might never have been tried without the emergency.

The BOS program was formalized by developing signing and striping standards and a policy on how bus drivers could use the lanes. This was a learning process and each corridor that is implemented has its own unique challenges that must be addressed. The state police had to be involved (1) so that bus drivers wouldn't get ticketed for driving on the shoulder and (2) to help develop regulatory signs that they would be comfortable enforcing. MnDOT had to change some practices, such as not using the shoulder to store snow when plowing and placing road construction signs on the adjacent grass, instead of on the paved shoulder.

Public reaction has been very positive—passengers perceive a greater time savings than they actually experience. Metro Transit sees value in time savings but even greater value in travel time reliability. Riders will heckle drivers if they aren't using the shoulders; at the same time, drivers have discretion on when to use the lanes and won't use them when conditions are unsafe (e.g., when icy). Cities and counties want to coordinate their projects with MnDOT's; an example is in Dakota County, where a BRT project starts on the shoulder of a state highway and continues on a county highway through several cities. The county championed the BRT service and the local cities paid for improvements within their jurisdiction.

Other regions visit MnDOT to see BOS in operation, but then have problems implementing it themselves. Information is not enough—organizational leadership and coordination is also needed. San Diego's plans halted due to objections by the California Highway Patrol (a change in state law was needed to allow shoulder use as a driving lane, even by authorized vehicles). Chicago only recently got a left-hand shoulder lane operational.

A pragmatic approach is best for these kinds of projects: get most of the job done for less money than trying to fix everything for a lot of money. Re-examine your 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 won't happen.

Team Transit holds quarterly meetings with Metro Transit and other transit agencies in the region, the highway patrol, and interested parties such as cities, counties, and the regional rail authority. It had been funded at $1 to $3 million annually, but was recently reduced to $0.5 million. Metro Transit and MnDOT had very little interaction before Team Transit was established; that action changed the relationship "immensely" in a positive way. It changed MnDOT culture from a highway agency to a multimodal agency. Culture change at MnDOT was supported, and the region earned a positive reputation nationally.

NEW YORK, NEW YORK

New York City has implemented a form of on-street BRT that is branded "Select Bus Service" (SBS). At the time of the interview, there were five SBS routes, with two more in development. Planning for the program went back 10 years, when MTA-New York City Transit (NYCT) began to become interested in BRT, wrote a scope for a planning study to figure out what BRT elements might work in New York City, and sent it 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 NYCDOT, which has responsibility for any on-street changes that are required, and provided an opportunity for the two agencies to build a relationship. It was clear that BRT would only work if the program worked for both agencies. All of the planning and design needed to be done in step with each other.

Follow-up studies—first under NYCT and more recently under NYCDOT—have addressed specific corridors. The biggest impetus to the program came in 2007, when both agencies got new leadership; both agency heads were interested in an aggressive approach to BRT.

The planning and design projects have been led by consultants. The agencies have a good idea of what they want at a conceptual level (e.g., high-quality bus lanes) and the consultants primarily focus on traffic analysis, recommending potential treatments for individual, and street design. NYCT has the resources in-house for service planning and scheduling. The SBS program has paved the way for better working relationships between NYCDOT and NYCT and their current relationship is viewed as good by both agencies.

NYCT utilizes several types of agreements for their projects. They have a broad, high-level MOU with New York City that, in a nutshell, states both agencies will work as hard as they can to get projects completed. They have added additional MOUs since they had some challenges in getting some of their project elements constructed, as City crews were not fond of completing small projects for transit such as curb extensions. The MOU provides the option for the City to cover the construction of small projects by NYCT forces.

NYCT has many different stakeholders involved in their projects. These include MTA (a state-level organization), NYCT staff, NYCDOT staff, New York State DOT staff, the MPO, and some of the city's 57 community boards. In addition, large hospitals, businesses, and schools along an SBS 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 obtains 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 their needs in a clearer way, and generally functions much 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 very 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 impacted parties would attend each meeting, all 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 SBS routes that were either operational or in some stage of planning at the time the interviews were conducted.

Once a route is ready to open up, there is advance outreach—both open houses and an on-street presence. Customer ambassadors are posted at every stop to explain how the fare collection system works. NYCT has an extensive in-system media list—a resource transit agencies don't usually have. Finally, there is a huge array of marketing pieces to inform the public about how their ride is changing.

There have not been any large issues that have cropped up during implementation, but instead there has been a large volume of small things: accommodating businesses with deliveries by tractor-trailer trucks, a building with a crane that wasn't there when the route was laid out, the need to move bus stops. An example of an unexpected hurdle encountered during a project was coordinating with NYU Hospital and two of its facilities along an SBS corridor. The hospital offered valet parking in the space where a bus lane would be located, so coordination was required to accommodate patients utilizing the valet services.

The agencies have learned a lot about allocating curb space—for deliveries, parking, right turns, bus stops—during planning and implementation. This wasn't something at the top of their radar when they started, but is now the most salient issue on any SBS project. They studied what other large cities were doing with bus lanes and found out what works and what doesn't:

- Offset bus lanes function much better.
- Red paint on bus lanes helps keep cars out of the lane.
- Overhead signage is what drivers can see.

Red-painted bus lanes were not something that the MUTCD allowed, but the FHWA allowed New York to experiment with them. The evaluation report was completed and submitted to FHWA, which accepted the results that the treatment is useful. (The use of red paint for transit use is expected to be added to the next edition of the MUTCD.) One key issue to overcome from New York's perspective was the durability of the paint. Initial paint treatments lasted less than a year, but after trying different materials and application processes, it now lasts 3–5 years.

Another regulatory hurdle was obtaining permission for automated bus lane enforcement. The New York State legislature passed a law in 2010 that applies to defined corridors in the city; automated enforcement could be used on all bus lanes at the time of the interview. NYCDOT is also pursuing a change to the city's traffic rules to clarify the use of bus lanes. Although the current rule is fully functional, it was felt it could be updated and clarified. New York already had the bus lane rule on the books when they started the SBS program, so they didn't need to start from scratch, but another city might need to create one if they have never had bus lanes before.

Siting bus stops is more art than science—a service planner that knows the route could lay out stops. The public consultation piece is challenging, because everyone thinks their neighborhood is more important and deserves a stop. Stop selection is not based 100% on ridership—if the street has a big cultural importance, it might be added. Once NYCT has identified general stop locations, NYCDOT goes through to make sure that there won't be any safety or operational (both roadway and sidewalk) problems with the proposed location. There is occasionally the need for give and take to come up with locations that both agencies can accept—this can involve moving a stop from one side of the intersection to the other or, sometimes, to the next street. Because the SBS routes use off-board fare collection, there needs to be sidewalk space available for the fare machines.

There was some concern from motorists prior to implementation about the effect on traffic, but once implemented, people say it is flowing approximately the same. That being said, one can always find someone who isn't satisfied. From the standpoint of transit operations, bus lane and parking restriction enforcement is crucial. However, the police department has other priorities that are more important. Therefore, minimizing the need for enforcement (e.g., through the use of red paint and overhead signs) and automating enforcement is helpful. When corridor-wide enforcement is needed, for example, after opening new bus lanes, NYCT pays for the extra policing effort. For more localized enforcement, at a specific intersection for example, staff in each borough know who to call at the local precinct.

Lessons learned from the SBS projects include:

- Good traffic data are critical to support design decisions, such as where bus lanes should go. In addition, it is important to have good parking occupancy data for both curbside parking and off-street lots to address stakeholder concerns.
- It is also critical to have a team member who is good at explaining the engineering side of the work in terms that all stakeholders can comprehend.
- It is beneficial to 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.
- It helped to make the first changes to the bus system in parts of the city that were more accepting of change, which gave better press to the initial SBS lines and helped ease the way for subsequent projects.
- 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.

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 (equivalent to a U.S. county), 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 signage), as well as with the pedestrian and bicycle office within the planning department.

As is the case throughout Canada, the federal government does not play a role in providing transit operating funding; instead, this is the responsibility of local or regional governments. Larger capital projects would receive provincial and possibly federal funding, but the city funds smaller-scale transit capital projects, particularly those under CAN$2.5

million which do not require a full environmental study. Most transit preferential projects fall into the small-scale category.

Ottawa is known for its off-street, grade-separated Transitway; however, this type of facility is not the focus of TCRP Project A-39. Nevertheless, the bus routes that travel on the Transitway also use on-street facilities at other points along their route. 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 in 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 implementations focus on these corridors. At the same time, OC Transpo uses input from bus drivers and others to identify other locations that could benefit from projects and takes 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, TSP had been implemented at approximately 50 locations citywide, using bus-mounted transponders that are detected by in-pavement traffic signal detector loops. TSP is primarily provided as a green extension, due to technological limitations of the city's signal controllers. Bus detection rates are not good, so the city was in the process of investigating alternative detection systems.

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

- *Phase reservice.* When 2–3 cars or a bus occupy a left-turn lane, the left-turn may be served twice within the same signal phase, both as a leading left turn and as a lagging left turn. 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 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 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 progress buses, 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 auto 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 roadways.* 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 streets 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 preferential projects. 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 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.

City policy now requires that bicycle facilities be included with all new and reconstructed roads. The preferred treatment is a bicycle lane or cycle track, but in constrained locations, shared bus and bike lanes are used. Although not the ideal solution, staff believes they are safer than the "before" condition, where buses, trucks, autos, and bikes would compete for the same space, and recent bus and bike lane implementations have experienced increased bicycle volumes.

Project opposition mostly comes from people who see transit preferential treatments as reducing auto level of service. OC Transpo's experience is that traffic settles down into a new equilibrium after a treatment has been implemented.

PORTLAND, OREGON

Portland's Transit Mall covers 5th and 6th Avenues, one-way streets running the length of downtown Portland. The mall originally opened in 1978, with two lanes dedicated to buses on each street, along with one travel lane that was forced to turn left off the mall every three blocks. Adding light rail to the mall at the end of the last decade produced significant changes for both transit and vehicular traffic operations; this was the topic of the interview.

The original concept for light rail operations on the mall was that the left-hand bus lane would become the light rail track location. Light rail stations would be located every fourth block at the existing block-long left-side curb extensions where no general traffic travel lane was provided. Buses would continue to operate in the right-hand bus lane. However, due to funding shortfalls, a local improvement district (LID) was conceived that would generate sufficient property tax revenue from areas in the vicinity of the transit mall. Before local businesses would approve the LID, they wanted something in return, which was a continuous general traffic lane along the mall to improve access to, and visibility of, businesses along the mall. This decision required changing both the transit and traffic operations concepts.

TriMet, the transit provider for Portland, has a long-standing, successful working relationship with the City of Portland. For this project, TriMet incorporated the City, the Portland Business Alliance (PBA), and Portland State University (PSU) as stakeholders in the project through a steering committee. The steering committee representatives assisted in working through funding hurdles, and made decisions on the light rail alignment and terminus. There were additional meetings that involved committees in the political and staff arenas, which addressed issues such as bus and rail operations, traffic signal operations, and integration plans. TriMet conducted hundreds of coordination meetings throughout the project, including one-on-one meetings with each specific stakeholder. There were separate business outreach activities associated with each light rail alignment scenario, along with a website and a general public involvement process. In hindsight, the project could have progressed more smoothly had the following stakeholders been identified and included earlier in the process: taxi representatives, bicycle advocates, armored vehicle representatives, and businesses on the temporary transit mall alignment during construction.

Special lane-usage signs were developed for traffic on the mall and side-street approaches to the mall. These were run past the Oregon Traffic Control Devices Commission, although it wasn't strictly necessary to do so. Special permission was required for the signal heads: a green up arrow was desired to reinforce the "no turns" message at certain intersections. This would normally require a 12-inch signal head, but the other signal heads would be 8 inches, which would have looked odd. A "T" pavement marking to indicate "trains only" was originally used, but was removed as it was not MUTCD-compliant.

TriMet would have liked to use raised domes as a barrier to separate the auto 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-inch white stripes) was used, in conjunction with overhead signs at intersections. Maintaining the striping is an issue, as buses cross over it in places to make left turns off the mall, which wears it away. Because the high-profile striping is safety-certified, it has to be maintained. In retrospect, using concrete for the transit lanes could have helped differentiate the two types of lanes. Also, in one part of the mall, streetcar tracks turn into the general traffic lane and then turn off a couple of blocks later, which sends mixed messages to drivers about whether they can drive on train tracks or not. When people do encroach in the transit lanes, they do so in a safe way, and bus operators are good at honking and using flashing lights to alert errant vehicles to get out of the transit lanes. Only a little police enforcement has been required.

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

- 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 on where buses would stop following reconstruction.

Transit mall maintenance costs are divided among the City, TriMet, and Portland Mall Management, a non-profit corporation funded by the City, TriMet, the Portland Business

Alliance, and Portland State University. The City maintains the automobile pavement markings, signage, 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.

The City and TriMet have worked together on many projects in the past and applied what they learned to the transit mall project. The number of projects and length of time the two agencies have worked together has helped keep the relationship strong. Staff keep core principles and each other's interests in mind; the agencies think of each other as customers to each other. The City and TriMet share controller cabinets, which is rare.

Bus operations are about 25% faster on average, compared to old operations. Most of this is due to the increased stop spacing and changes to better group bus routes together that would share sets of stops. The revised bus operating/merging pattern and reductions in the number of buses using the mall also contributed to the increased speeds.

TriMet suggests to other agencies pursuing a similar project to plan for adequate time to vet all design options. Additionally, agencies should establish adequate milestones with expected outcomes and plan to have contingencies built into the schedule to address challenges that arise throughout the project. It is also recommended to provide good follow-up with stakeholders to address punch-list items after the opening of the project to make certain things are still going well and that maintenance agreements are clearly defined and followed. For example, Portland experienced a major snowstorm right after the opening of the project and they didn't have an agreement with the City to address snow removal, since big snowstorms are rare in Portland.

SALT LAKE CITY, UTAH

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 the interview. 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. These lanes narrow to a one-lane cross-section with bi-directional operation prior to most signalized intersections, where there was insufficient right-of-way to provide dual left-turn lanes and two transit lanes.

Route 35M is a cross-town route on the street "3500 S" that connects the community of Magna to two light rail stations. The corridor is one of UTA's higher-performing bus routes, with approximately 4,500 daily bus riders. Most of 3500 S is also a state highway, owned and maintained by the Utah DOT, with Salt Lake County performing maintenance on the system used to provide traffic signal pre-emption for the fire department and TSP for Route 35M.

The region's long-range transportation plan identified the corridor as a future light rail or BRT corridor. When UDOT developed a widening project for 3500 S, they approached UTA to make it multimodal. UTA determined through the UDOT planning process that BRT was the best fit for the corridor, given the existing land uses and available budget. UDOT worked with UTA to implement the center bus lanes, including traveling to Vancouver to see the B-Line median lane in operation there, and contracting with the University of Utah to simulate bus lane and TSP operation. The traffic analysis helped convince UDOT that the center lane wouldn't significantly affect the roadway and that it might even benefit auto traffic. The region's prior experience with TSP and center median stations for light rail also helped smooth the way for the same things for BRT.

The center bus lane improvements (primarily raised curb where the bus lane is adjacent to opposing traffic and islands for bus stops) were paid in large part by UTA. BRT stations were paid for through Congestion Mitigation and Air Quality (CMAQ) funds. Traffic signals were already TSP-ready, but the special-purpose buses ordered for the route needed to have TSP equipment installed, and UTA contracted with the county to program TSP into their signal preemption equipment. UTA funded the traffic analysis focusing on bus lane and TSP operations. UDOT covered most of the other project costs as part of the overall roadway widening project.

Public involvement efforts for the center bus lanes were incorporated into public involvement for the overall roadway widening project. Given that no travel lanes or parking was taken to create the bus lanes, there was no major objection to that element of the project. Nevertheless, UTA met with businesses and the public an "awful lot" during the UDOT study. UTA also did a lot to market the BRT route before opening, including billboards, mail-outs with free transit tickets, and appearances at local festivals and parades, although nothing specific related to the center bus lane.

The single-lane, bi-directional bus lane operation at traffic signals was modeled during the planning process using microsimulation. The simulation results showed that bus operations would be substantially better with the bi-directional operation than if buses had to mix with the left-turning traffic, and operating experience has confirmed the simulation results. The bi-directional lane is controlled by standard light rail signals (vertical and horizontal bars) placed both at the entrances of the bi-directional lanes (upstream of the signalized intersections) and at the signalized intersections themselves. UTA believes the bi-directional operation works well, especially under 15-minute headways. UTA has not received any complaints from bus drivers about the bi-directional lanes except that sun glare during certain times of the year makes it difficult for bus drivers to see the bus signals.

Local cities and Salt Lake County have been happy since implementation. A local police department has had some issues, as patrol cars have gotten stuck trying to drive over the curbs (presumably while trying to make mid-block U-turns).

The region has a culture of working together (UTA, UDOT, MPO, local jurisdictions). In this case, UDOT approached UTA about making their project multimodal, and both the city and county worked to make coordination with UTA seamless during project development. Although UDOT and UTA have very 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 saved complexity and time by avoiding the need whenever possible to elevate decisions to higher levels in the respective organizations. Having a good partnership with the DOT project manager is essential.

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. There was a need to reduce—or at least maintain—transit operating costs, which is a challenge in the second-densest city in the U.S. In addition, there was a need to address the two biggest passenger complaints: crowded and unreliable service. The Transit Effectiveness Project (TEP) was established to address these challenges.

During the initial planning phase of 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.

Agency partners during the planning stage included a number of SFMTA departments, including transit, Sustainable Streets (traffic engineering), and Livable Streets (pedestrians and bicycles); the Controller's office; the Mayor's office; and the San Francisco County Transportation Authority (SFCTA). The mayor and other elected officials were very involved and supportive of the project. Funding for the planning effort came from the Controller's office and a consultant was used to help develop the plan.

The solution identified was to redesign the system to better meet travel patterns and to reduce crowding, and to develop bus priority projects to create a more reliable system. A number of potential projects were discussed and have evolved based on community input and implementation realities. For example, the idea of bus-only lanes on each rapid bus corridor has evolved into providing bus-only lanes at specific locations.

At the time of the interview, the project was in a 2-year environmental review process under the California Environmental Quality Act that was analyzing the entire TEP as one project, which meant that none of the proposed service changes or bus priority projects could be implemented before the review is completed. In anticipation of a successful review, SFMTA was coordinating a funding plan that includes the SFCTA and the regional 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., with Public Works, to get curb extensions constructed in conjunction with repaving projects). As of December 2014, many of the projects identified in the TEP had been incorporated into the Muni Forward program for implementation (SFMTA 2014).

Two pilot projects outside the environmental review process had already been implemented. First, SFMTA is testing whether stop consolidation improves reliability by removing approximately half the stops on the 76X bus route. Second, SFMTA is testing a red transit lane to see if it improves motorist compliance with the lane and thus improves transit reliability. SFMTA's transit division will coordinate implementation when it happens, and its capital planning and construction division will do any construction work involving overhead wire on trolleybus and light rail corridors. The Public Works Department will handle other construction projects. Finally, SFMTA's Sustainable Streets Department will coordinate legislation and other activities associated with parking loss.

SEATTLE, WASHINGTON

King County Metro operates a form of BRT branded as RapidRide. At the time of the interview, 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, 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-minute headways during the morning and evening peak and 15-minute 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 DOT (WSDOT), share fiberoptic lines along Rapid Ride corridors.

A set of “Speed and Reliability Partnerships” were developed for the RapidRide project. The partnerships were contractual, formal interagency agreements which 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 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 to 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 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 tradeoffs to the vehicular and pedestrian operations were acceptable. As a result, this engineer became a champion for the concept. Finding a champion at other, more-conservative agencies 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 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, and they provided input on the project scope as 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 bi-weekly 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 schedule estimates to provide input on what their 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.

The only delay that occurred on the project came from customer comments that came toward the end of the project when the removal process was underway. Re-evaluation of stop locations was conducted based on customer comments, which could change the scope of the project depending on the specific location.

Some of the hurdles in the project involved initial comments from the Service Implementation Committee that some members felt the changes were too severe. Additionally, a small minority of the fixed-route operators felt the project was detrimental to the public. Addressing these concerns was additional time not anticipated by the project.

Upon completion of the first phase of the project, the fixed route operators began to see that removing the stops did in fact improve the speed and reliability of the buses, which was a real breakthrough moment on the project.

For internal agency groups, it is important that they understand the project and why it is being done. 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, as they are the face of the agency and often the first point of contact for a customer with a question. It is also important to plan for some flexibility. For example, some comments were received well after the comment period ended, but by being flexible with the customers and, in some cases, adjusting the project, the public's trust in the agency was increased.

The initial plan development would have benefited by having an all-inclusive list of all social service agencies, support groups, medical offices, and similar locations. For example, one particular group of stops to be closed was adjacent to a battered women's shelter. Many of these women are dependent on transit, but the shelter's location was unlisted for security reasons. It was not until well into the comment period that STA was made aware of the shelter and altered the plans accordingly.

VANCOUVER, CANADA

TransLink is the transportation authority for the Vancouver region. Through several operating companies, it operates the region's transit network, including bus, heavy rail, commuter rail, ferry, and demand-responsive transit. It also provides planning and funding for other modes—arterial-level streets and pedestrian and bicycle facilities—and owns several river crossings and freight roadways. The province of British Columbia owns the provincial highway network, including most significant roadway bridges, and is the owner of the provincial traffic act, the legal basis for bus turn exemptions, yield-to-bus laws, etc. Local cities and municipalities operate the remainder of the roadway network.

King George Boulevard B-Line

TransLink has operated on-street BRT routes ("B-Lines") since the late 1990s. At the time of the interview, a new B-Line was being planned for King George Boulevard in the City of Surrey, in the southern part of the region. Once the primary route from Vancouver to the U.S. border, the former King George Highway is being transformed into an urban boulevard, and transit preferential 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 it is not a transit service provider itself, there is strong support in Surrey to help improve transit service. The city's capital plan focuses, for example, on implementing transit preferential strategies. Although Surrey participates in project cost-sharing, 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 SkyTrain. One pair of queue bypasses already existed along the route and two more were planned to be constructed prior to opening. At some point in the future, when the route is extended south to White Rock, just north of the U.S. border, more queue bypasses will be constructed at congested intersections. A consultant study has identified potential locations for preferential strategies. TSP is a future 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 included narrowing lanes to urban street widths (11.5 to 12 feet); adding bike 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. Signal timing in the corridor will also be adjusted to better progress peak-direction traffic. One of the intersections where queue bypass lanes will be installed is also the municipality's highest-crash locations, so the city will be looking closely at the impact of the lanes on intersection safety. TransLink is funding the project, while the city is designing the project.

There has been (and continues to be) a lot of planning for the project and the city's main lesson learned to date is that one needs to plan far in advance for a project of this scale.

Port Mann ExpressBus

At the time of the interview, the province was completing the Gateway Program, which includes widening 22 miles of the Highway 1 (Trans-Canada Highway) freeway, including adding managed lanes in each direction, and replacing the old five-lane Port Mann Bridge with a new, tolled ten-lane bridge. The old bridge was a significant bottleneck on the highway and no transit service operated over it because of the long delays and no opportunity to provide transit priority. With the opening of the managed lanes, the new bridge, and a new transit center toward the east end of the project, TransLink has started a new Port Mann ExpressBus service that uses the managed lanes, connecting temporarily to the Braid SkyTrain rail station. When the project is fully complete, the bus will take advantage of a bus-only exit/entrance from the managed lanes to end at the Lougheed Town Centre SkyTrain station and transit hub.

The Gateway Program was an initiative of the British Columbia Ministry of Transportation and Infrastructure (MoTI) to address congestion issues in the southeastern portion of the Vancouver region. In addition to the freeway widening and bridge replacement, the project includes freight mobility components. MoTI was determined to accommodate future transit as part of the freeway project—not just within the TransLink service area, which ends around the eastern project boundary, but also to communities farther to east. Modeling indicated a market there for park-and-ride–based service, relatively modest, but significant enough to justify additional widening on the bridge (from eight lanes to ten lanes).

During planning, three services were envisioned over the bridge: from Langley to Burnaby (the current ExpressBus service), from Surrey to Burnaby, and from Surrey to Coquitlam. The latter two services have not yet been implemented, but the bus route was adjusted about a year after opening to take advantage of managed lane on- and off-ramps that provided an opportunity to stop in Surrey.

TransLink and MoTI had experience with bus operations in managed lanes elsewhere in the region, so they felt they had sufficient design guidelines available when the Highway 1 lanes were being designed. They had not heard any issues from bus drivers since the ExpressBus service started. TransLink was pleased with the initial ridership, with parking facilities operating at 70% capacity.

Other Preferential Strategies

Other preferential strategies used in the region came up during the interview:

- *Bus shoulder running.* Buses are allowed to use the shoulder on a portion of the Highway 99 freeway, which approaches Vancouver from the south. The intent is that only transit buses should use the shoulder, as "very stringent training" is involved, but legally any bus can use the lanes. They have noted non-transit buses (e.g., casino buses) using the lanes at speeds of 120 km/h and higher (the speed limit is 100 km/h).
- *Bus lanes.* Hastings Street is a major east–west street connecting downtown Vancouver to Simon Fraser University in Burnaby and is planned for a future B-Line route. Bus volumes in the Burnaby section of the street would make the curb travel lane a *de facto* bus lane, but making it an actual bus lane has proven difficult, due to the need to provide on-street parking for merchants.
- *Transit signal priority.* TransLink has experimented with TSP along a section of Main Street in Vancouver, but has not seen significant benefits from it. Further challenges are the mix of signal equipment used in the region and the difficulty of making a business case for single-intersection improvements, as the cost to equip the bus fleet with the necessary equipment is significant.

The interviewees also noted that institutional issues play a role in how easy or difficult it is to implement transit preferential strategies. They contrasted Calgary, where the region is essentially one city and the city looks after all transit functions, with more diverse regions like Vancouver, with a number of municipalities, each with its own infrastructure and policies, along with a transit operator that is a regional organization. They felt that transit projects would flow easier in Calgary than in the Vancouver region. TransLink has a regional responsibility, but doesn't have the corresponding authority.

LEAGUE OF AMERICAN BICYCLISTS

The mission of the League of American Bicyclists is "to promote bicycling for fun, fitness and transportation and work through advocacy and education for a bicycle-friendly America." The league's policy director was interviewed on his thoughts on different transit preferential strategies, from the bicyclist viewpoint. He also suggested contacting the National Association of City Transportation Officials (NACTO) for more of a planning and engineering perspective, which resulted in the interview summarized next.

Bicyclists want to be able to connect to transit and to bring bicycles with them on the vehicle. This benefits transit, by extending the catchment area of transit service. Bicycle parking and storage at stations is also important.

On-street, the ideal situation is a separated physical space for bicyclists that is buffered from traffic (e.g., cycle tracks, buffered bicycle lanes). Where that isn't possible, then the conflict between stopped buses and bicycles should be addressed. A common conflict is where bicycles try to pass buses on the right. There should be visual guidance to pass on the left, along with physical space to allow passing. Where bicycle lanes exist, dashing the line at bus stops helps to signal the potential conflicts and need for passing. Washington, DC has some shared bus/bicycle lanes which get mixed reviews, mainly because of auto use of the lanes for right turns or, simply, unauthorized use. Chicago has used education programs for bus drivers to make them more aware of bicyclists.

In terms of signal timing, timing to progress bicycles is ideal; since bicyclists and buses move at approximately the same average speed, it would be interesting to see if timing that works for buses would also work for bicycles. Shorter cycle times or longer green times to benefit buses would also benefit bicyclists.

Intersection design should minimize the potential for right-hook and left-hook motor vehicle–bicycle crashes and should consider bus–bicycle conflicts as buses pull into and out of stops. Curb extensions should not cut off the bicycle lane.

Turning prohibitions and exemptions for buses should also benefit bicycles, as long as bicycles don't have to detour. Removing turning conflicts (particularly right turns) is desirable from a bicyclist standpoint. Bus gates, or streets that permit bicycles to travel between neighborhoods, would act as a sort of bicycle boulevard, while reducing other vehicular traffic on the route.

NATIONAL ASSOCIATION OF CITY TRANSPORTATION OFFICIALS (NACTO)

NACTO is a non-profit organization "that represents large cities on transportation issues of local, regional and national significance." The organization developed the *Urban Bikeway Design Guide,* now in its second edition, to provide guidance on successful international bicycle facility treatments that were not addressed in AASHTO's bicycle design guide (AASHTO 2012). The interviewee was NACTO's project manager for the development of the guide and was asked to give a bicyclist perspective on various transit preferential strategies.

Echoing what the League of American Bicyclists interviewee stated, the ideal situation for a bicyclist would be a facility buffered from other traffic. At bus stops, the facility would wrap around the bus stop platform, to avoid the need to pass buses on the left. When a buffered facility is not possible, the following are alternatives:

- On one-way streets, consider placing bus lanes on the right side and bike lanes on the left side, thereby providing exclusive facilities for each mode and preventing bus–bicycle conflicts at bus stops. However, this design can complicate making right turns for bicyclists.
- A full-time curbside shared bus–bicycle lane provides a route guidance function, but otherwise functions similarly to mixed traffic. A curb lane used for peak-period bus and bike use and off-peak parking and bike use would be similar to the full-time shared bus–bicycle lane, but could also have potential issues depending on the level of parking enforcement. The bus volume would play a role in how well the lane functioned for bicycles. There is a tendency in some cities to combine everything in one lane, but the interviewee doesn't really support shared bus–bicycle lanes.
- A median bus–bicycle lane is something that has been used internationally (e.g., Paris). It works better than curbside lanes, but also causes some issues: "99% smooth sailing, 1% terrified," "the jury's still out as to whether we'd recommend it." Austin has a 2-way cycle track co-located in the median with its commuter rail line.
- Placing a bicycle lane to the right of the bus lane would probably not be comfortable at bus stops.

Lane widths often come up as an issue. Transit agencies want wide (e.g., up to 14 feet) lanes for their buses, which results in less flexibility to work with the rest of the street to put in high-quality bike facilities.

Curb extensions create conflicts, whether they are used near-side or far-side. When used, dashed bike lane markings should show the bus/bike mixing space. Seattle has provided cut-throughs for bicycles at some far-side bus boarding islands which allows bicyclists to go around the bus stop instead of mixing with buses—a preferable alternative to a curb extension that stops the bicycle lane or causes bikes to swerve into traffic.

In terms of traffic signal timing, more green time is a win/win, unless high bicycle volumes exist on the side street. Shorter cycle lengths are beneficial, as it shortens bicycle delay and improves pedestrian compliance with signals, thus reducing pedestrian–bicycle conflicts.

Bus progression might hurt or help bicycle travel, depending on the situation—San Francisco has done a “green wave” for bicycles. Portland hasn’t done that yet, but does provide bike actuation on minor-street approaches to traffic signals. TSP is desirable, as it also benefits bicyclists traveling in the same direction, except when high bicycle volumes exist on the side street. Allowing bicycles to use queue jumps could be a boon for bicyclists and could help pedestrians as well, if they’re also given a head start.

Traffic engineering treatments such as turn exemptions and prohibitions are mutually beneficial. An example is a short contraflow lane on Boston’s Silver Line south of downtown that takes bikes and buses over a highway, to the benefit of both modes.

Appendix C. Transit Signal Priority Impact Assessment

INTRODUCTION

The impacts of transit signal priority (TSP) vary depending on their design and traffic characteristics (e.g., intersection geometry, presence of queue jump lanes, presence of exclusive lanes, traffic volumes and patterns), transit characteristics (e.g., service frequency, bus stop location), signal control system features and timings (e.g., cycle length, green times), and TSP features (e.g., minimum green extension, red truncation, rules for granting priority). The literature review summarized in Chapter 2 showed that the implementation of TSP strategies can result in lower delays for buses and vehicles that travel in the same directions, but can have negative impacts on the delays of the cross (i.e., non-priority) streets. The magnitude of this negative impact varies from insignificant delay increases to major ones, especially when the cross-streets operate close to saturation.

The assessment of TSP strategies has been mainly based on simulation and field studies. Simulation studies are data-intensive and, as a result, time-consuming (Rakha and Zhang 2004, Ahn and Rakha 2006). In addition, most of these studies do not accurately incorporate TSP logic and features, and thus fail to realistically model the TSP systems. Field tests typically have high costs (i.e., equipment, extra delays to traffic during the experiment), are time consuming, and the findings cannot be easily generalized because they depend on the study site characteristics (Ahn, Rakha, and Collura 2006). Analytical models offer a straightforward and less data-intensive approach for assessing TSP. Existing analytical models (Sunkari et al. 1995; Liu, Zhang, and Cheng 2008) ignore random and oversaturation delays. As a result, they cannot accurately estimate the impact of TSP when conditions are close to or over saturation, which is the case for non-priority approaches that operate close to saturation. Other analytical approaches summarized in the literature (e.g., Kittelson & Associates, Inc., et al. 2007) focus on the benefits of TSP on the priority movements during one signal priority cycle.

This appendix describes an analytical approach for estimating the impacts of TSP at signalized intersections using the analysis procedures of the *Highway Capacity Manual* (HCM 2010). The proposed methodology provides adjustment factors for estimating the delay under TSP from the HCM 2010 estimated delay under normal operating conditions. The methodology was originally developed in an earlier project (Christofa and Skabardonis 2011) and was extended and refined in this study.

THEORY DEVELOPMENT

TSP implementation does not affect negatively the intersection approach (typically an arterial through movement) served by the priority phase(s). It is likely that it will even benefit the priority approaches due to the additional green provided, depending on the progression characteristics of the arterial under consideration. However, TSP strategies have a significant impact on the delays of the non-priority phases (i.e., cross-streets). The

HCM 2010 formulae allow the delay impact to be estimated, given a particular change in green time due to TSP.

According to the HCM 2010, the control delay d for a lane group at a signalized intersection is given by the following formula (HCM Equation 18-19):

$$d = d_1 + d_2 + d_3 \tag{1}$$

where

- d_1 = uniform delay, the average delay that would occur if vehicles arrived randomly throughout the traffic signal cycle;
- d_2 = incremental delay, delay caused by random, cycle-by-cycle fluctuations in demand that occasionally exceed capacity, plus delay caused by sustained over-capacity demand; and
- d_3 = initial queue delay, delay due to a residual queue of vehicles resulting from over-capacity demand in a preceding analysis period.

The uniform delay is calculated as (HCM Equation 18-20):

$$d_1 = \frac{0.5C(1-[\mathrm{g/C}])^2}{1-[\min(1,X)\ g/C]} \tag{2}$$

where

- d_1 = uniform delay (seconds per vehicle),
- C = traffic signal cycle length (seconds),
- g = effective green time (seconds), and
- X = volume-to-capacity ratio (unitless).

The incremental delay is calculated as (adapted from HCM Equation 18-45):

$$d_2 = 900T\left[(X-1) + \sqrt{(X-1)^2 + \frac{8kIX}{cT}}\right] \tag{3}$$

where

- d_2 = incremental delay (seconds per vehicle);
- T = analysis period length (hours) = 0.25;
- X = volume-to-capacity ratio (unitless);
- k = incremental delay factor, accounting for actuated traffic signal phasing, from HCM Equation 18-41 (unitless);

I = upstream filtering adjustment factor, accounting for the effect of an upstream traffic signal on vehicle arrivals, from HCM Equation 18-3 (unitless); and

c_A = average lane group capacity (vehicles per hour).

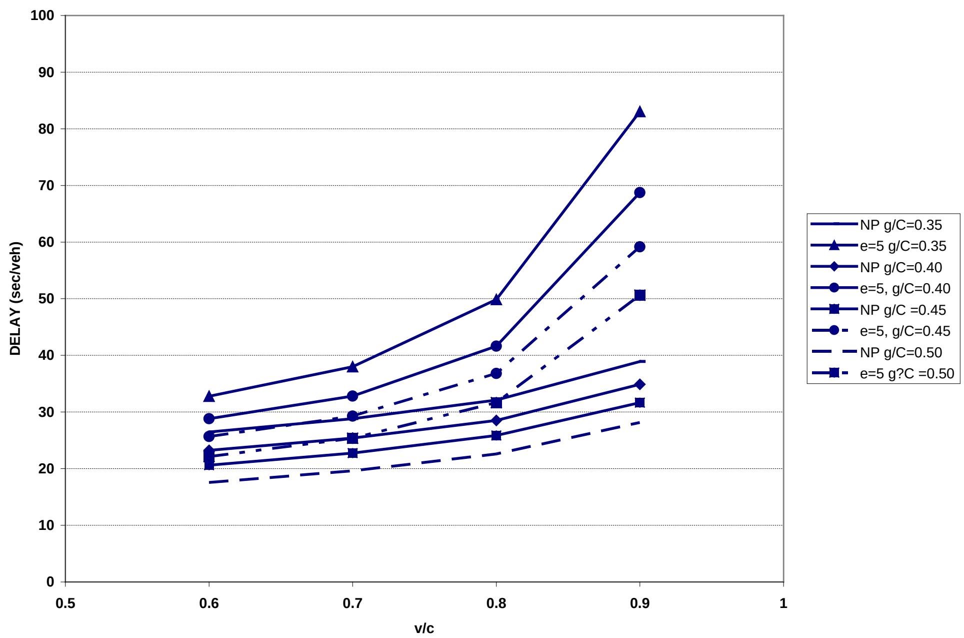
HCM DELAY ADJUSTMENT FACTOR DEVELOPMENT

For this work, the initial queue delay was assumed to be zero (i.e., all demand was served in the prior 15-minute analysis period). The incremental calibration delay factor k was assumed to be 0.50 (fixed-time signals) and the upstream filtering adjustment factor I was assumed to be 1.00 (uncoordinated approaches).

A typical two-phase signalized intersection was used to obtain estimates of the impact that common TSP strategies have on the cross-street delays. The impacts were evaluated for several cycle lengths ranging from 70 to 120 seconds, cross-street green time–to–cycle length (g/C) ratios from 0.35 to 0.50, and volume-to-capacity ratios from 0.60 to 0.90. Delays were calculated for (a) no TSP, (b) TSP extension of the green time for the main street by 5 seconds (or equivalently, truncation of the red time for the main arterial phase by 5 seconds), and (c) TSP green extension (red truncation) for the main street by 10 seconds, resulting in a total of 288 cases.

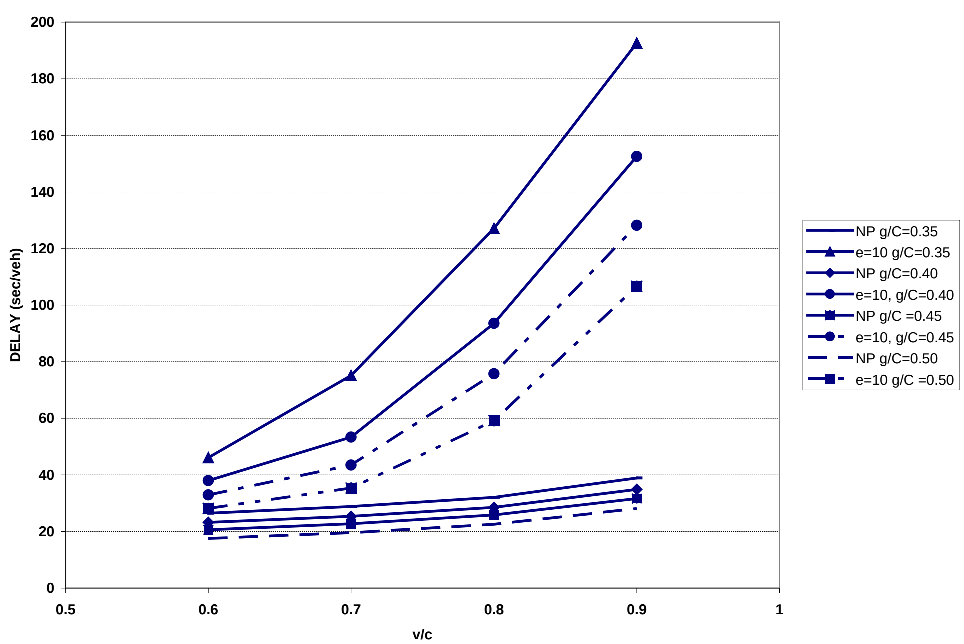
Figures C-1 and C-2 show the delays on the cross (non-priority) street for a cycle length of 90 seconds for no TSP and two TSP scenarios. As shown in these figures, the delay impact to the cross-street are higher on cross-streets with high degrees of saturation (i.e., high volume-to-capacity ratios). Also, the higher the g/C ratio, the lower the delay impact to the cross-street. This can be explained by the fact that the higher the g/C ratio for the cross street, the smaller the chance for the cross-street to operate close to saturation and forming residual queues that lead to significant increases in delay. In addition, the delay impact is much higher for greater reductions in the green time of the cross-street (i.e., longer extension or truncation intervals), as expected.

The ratio of *delays with TSP* and *delays without TSP* can be used to develop adjustment factors which, when multiplied with the delay experienced when no priority is provided, estimate the impact of specific TSP strategies on the cross-street for each combination of v/c ratio, g/C ratio, cycle length, and TSP (i.e., green extension or red truncation) interval length. Tables C-1 through C-4 show estimated adjustment factors for v/c ratios of 0.6, 0.7, 0.8 and 0.9; g/C ratios of 0.35, 0.40, 0.45 and 0.50; cycle lengths from 70 to 120 seconds; and extensions of 5 and 10 seconds. The use of such factors allows for the quick estimation of delays on cross-streets and the evaluation of TSP strategies without the need for intensive calculations or time-consuming simulations.



Notes: v/c = volume-to-capacity ratio, g/C = green time to cycle length ratio, NP = no priority, e = green extension time in seconds.

Figure C-1. Cross-Street Delays by TSP Strategy (90-second Cycle Length, 5-second Extension)



Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, NP = no priority, e = green extension time in seconds.

Figure C-2. Cross-Street Delays by TSP Strategy (90-second Cycle Length, 10-second Extension)

Table C-1. HCM Delay Adjustment Factors for v/c =0.60

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	1.36	*3.25*	1.35	*2.36*	1.34	*2.08*	1.34	*1.81*
80	1.27	*2.05*	1.28	*1.85*	1.29	*1.75*	1.30	*1.74*
90	1.24	*1.74*	1.24	*1.63*	1.25	*1.60*	1.26	*1.60*
100	1.21	*1.56*	1.21	*1.51*	0.99	*1.50*	1.23	*1.52*
110	1.18	*1.46*	1.18	*1.43*	1.19	*1.43*	1.21	*1.45*
120	1.16	*1.39*	1.17	*1.38*	1.17	*1.38*	1.19	*1.40*

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

Table C-2. HCM Delay Adjustment Factors for v/c =0.70

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	1.54	*5.57*	1.46	*4.10*	1.43	*3.24*	1.43	*2.73*
80	1.40	*3.48*	1.36	*2.74*	1.35	*2.25*	1.35	*2.09*
90	1.32	*2.61*	1.29	*2.10*	1.29	*1.91*	1.29	*1.81*
100	1.26	*2.00*	1.25	*1.78*	1.25	*1.67*	1.25	*1.64*
110	1.22	*1.75*	1.21	*1.60*	1.22	*1.56*	1.23	*1.54*
120	1.19	*1.57*	1.19	*1.49*	1.19	*1.46*	1.20	*1.47*

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

Table C-3. HCM Delay Adjustment Factors for v/c =0.80

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	2.18	7.78	1.84	6.03	1.78	5.53	1.67	4.74
80	1.76	4.23	1.61	4.37	1.55	3.84	1.50	3.39
90	1.55	3.96	1.46	3.28	1.42	2.93	1.40	2.62
100	1.42	3.08	1.37	2.61	1.35	2.37	1.33	2.18
110	1.36	2.58	1.30	2.19	1.29	2.01	1.29	1.90
120	1.29	2.16	1.26	1.92	1.25	1.81	1.25	1.72

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

Table C-4. HCM Delay Adjustment Factors for v/c =0.90

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	**3.07**	**8.60**	**2.77**	**7.33**	**2.61**	**6.73**	**2.43**	**6.18**
80	**2.49**	**6.23**	**2.28**	**5.52**	**2.14**	**5.05**	**2.04**	**4.73**
90	**2.13**	**4.95**	**1.97**	**4.37**	**1.87**	**4.05**	**1.80**	**3.79**
100	**1.88**	**3.98**	**1.73**	**3.55**	**1.69**	**3.33**	**1.64**	**3.15**
110	**1.69**	**3.37**	**1.59**	**3.01**	**1.57**	**2.88**	**1.52**	**1.78**
120	**1.39**	**2.53**	**1.51**	**2.66**	**1.47**	**2.49**	**1.44**	**2.38**

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

The adjustment factors shown above apply for estimating the delays on those signal cycles with transit priority. The average delay (seconds per vehicle) on the cross-streets can be obtained as follows from Equation (4), which can be rearranged into Equation (5):

$$d_{cs} = d_{cs,Bus}P(\text{bus}) + d_{cs,NoBus}P(\text{no bus}) \tag{4}$$

$$d_{cs} = d_{cs,NoBus}[1 + P(\text{bus})(f_{TSP} - 1)]$$

where

d_{cs} = average cross-street delay (seconds per vehicle),

$d_{cs,Bus}$ = cross-street delay in cycles with a bus arrival (seconds per vehicle),

$d_{cs,NoBus}$ = cross-street delay in cycles without a bus arrival (seconds per vehicle),

P(bus) = probability of a bus arrival during the cycle (decimal),

P(no bus) = probability of no bus arrival during the cycle (decimal) = 1 – P(bus), and

f_{TSP} = cross-street delay adjustment factor from Tables C-1 through C-4 (unitless).

Assuming that buses arrive on schedule, the probability of a bus with frequency $1/H$ arriving during one cycle of length C is:

$$\text{P(bus)} = \frac{C}{H} \tag{6}$$

where

P(bus) = probability of a bus arrival during the cycle (decimal),

C = cycle length (seconds),

H = bus headway (seconds).

APPLICATION

The proposed methodology was applied at a real-world signalized intersection with TSP (El Camino Real and 25th Avenue in the San Francisco Bay Area) using field and simulated data. The test intersection was a four-phase signalized intersection that operated at a cycle length of 90 seconds. TSP is provided to buses traveling southbound on El Camino Real, with a priority interval of 5 seconds. The buses operate with 10-minute headways. The critical cross-street approach has a g/C ratio of 0.20 and operates with a v/c ratio of 0.57.

According to simulation runs performed at the site to evaluate TSP strategies (Liu et al. 2004), the average vehicle delay for the cross street is 39 seconds per vehicle when a green extension of 5 seconds is employed. The HCM signalized intersection method estimates a non-TSP delay of 38.6 seconds per vehicle for all cross-street movements and a delay with TSP of 57.2 seconds per vehicle. The average delay within an hour is obtained from Sunkari et al. (1995), taking into account the bus frequency.

$$d_{cs} = d_{cs,Bus}\mathrm{P(bus)} + d_{cs,NoBus}P(\text{no bus})$$

$$d_{cs} = (57.2)(90/600) + (38.6)(1 - [90/600]) = 41.4\ \text{s/veh}$$

This value is in close agreement with the simulated delays (39 seconds per vehicle). Furthermore, it is shown that the delay increase due to TSP is about 19 seconds (or 50%) during the cycles that buses arrive receive priority, but on average over one hour, the delay increase is only 4 seconds (10%) and the level of service remains the same.

IMPACT OF TSP ON LEVEL OF SERVICE (LOS)

The impact of TSP strategies on the cross-street's LOS can be determined by comparing the average delays of vehicles on the cross-street with and without provision of TSP. Figure C-3 illustrates the impact on cross-street LOS for a 10-second provision of TSP (green extension or red truncation) to buses traveling on the main street with a frequency of 6 buses per hour for all the tested combinations of v/c ratio, g/C ratio, and cycle lengths (144 scenarios). It can be seen from the figure that the cross street LOS remained unchanged when the initial (without TSP) was LOS A or B. As the baseline traffic conditions worsen (initial LOS C or D), the provision of TSP can degrade the LOS on cross-streets by one level, and up to two levels at low g/C ratios (e.g., from LOS C to LOS D/E). The results depend on the TSP features and the transit vehicle frequency.

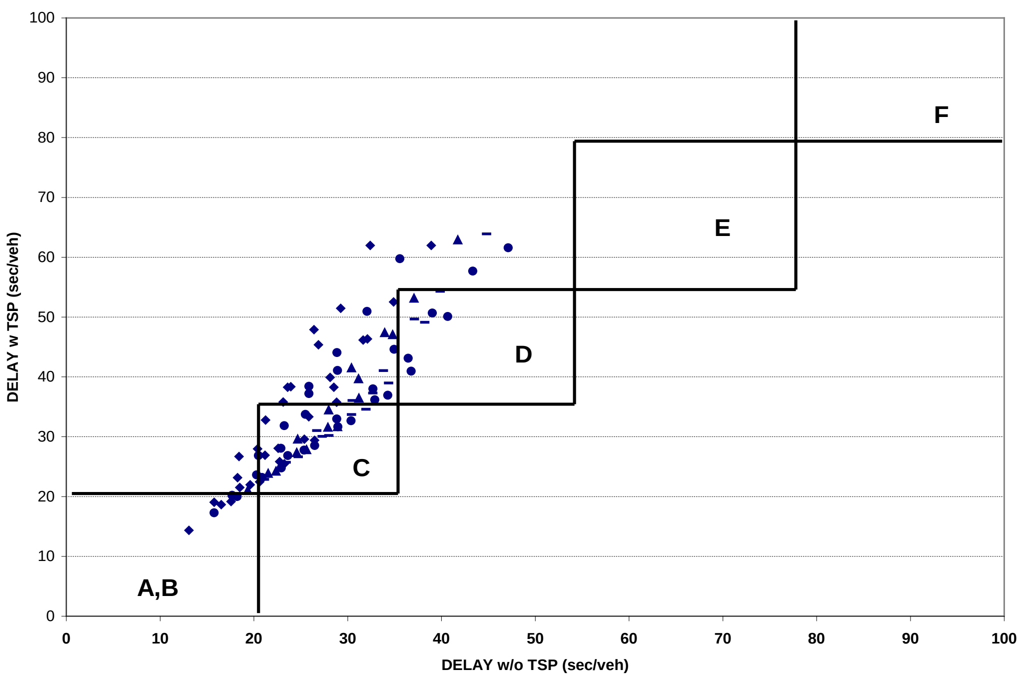
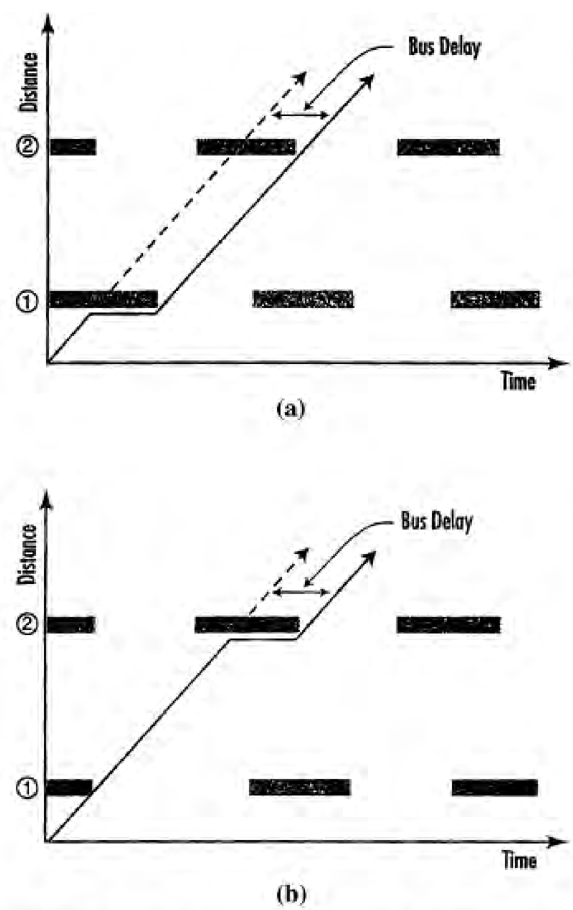


Figure C-3. Impact of TSP on Cross-Street LOS (10-second Extension)

SIGNAL PROGRESSION CONSIDERATIONS

The decision to provide transit priority at isolated traffic signals considers primarily the availability of spare green time, that is, the time available in the cycle length after serving the traffic demands at the intersection approaches. Sufficient green time ensures that no oversaturation, and corresponding long delays, would occur for the non-priority traffic movements. However, the implementation of TSP at an intersection that is part of a coordinated signal system should also consider the bus arrival time at the downstream intersection(s) (Skabardonis 2000).

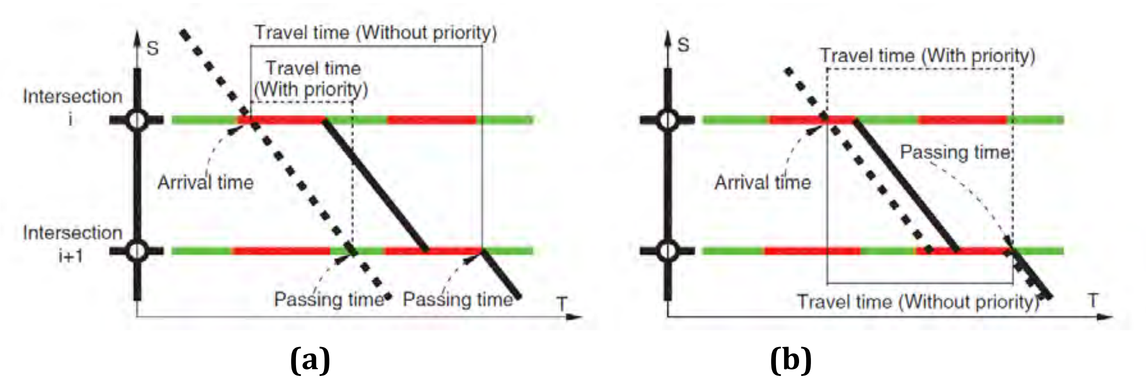
Granting transit priority at the upstream intersection may result in additional delay at the downstream intersection for the bus, thus achieving no net delay benefit for the bus. Figure C-4 shows an example of "wasted" TSP at Intersection 1, in a simple case where the bus does not stop to serve passengers. Because the bus must stop at Signal 2 downstream (Figure C-4b), the bus delay is the same as that in the case of no TSP (Figure C-4a). Therefore, the signal settings at the adjacent intersections will either need to be adjusted to account for effects of TSP on bus arrivals, or TSP should not be granted at the subject intersection under this timing plan.



Source: Skabardonis (2000).

Figure C-4. Example of "Wasted" TSP at Intersection 1.

The arrival of a bus at the downstream intersection, given that priority is granted at the upstream intersection, depends on several factors, including the bus travel time, bus stop dwell time (if any), intersection signal settings (e.g., offset, green times), and the amount and type of TSP treatment (Wa et al. 2013). Figure C-5 illustrates the impact of the type of progression (green extension or red truncation) on the total bus delay. In Figure C-5a*,* after a bus receives priority (green extension) at intersection *i,* it can proceed through intersection *i* + 1 without delay (trajectory shown by the dotted line), and the total travel time is reduced dramatically compared with the no-priority case at the upstream intersection (trajectory shown by the solid line). However, in Figure C-5b, the bus receives a priority treatment (red truncation) at intersection *i* and arrives at the next intersection *i* + 1 during the red time, and the total delay is unchanged compared with the no-priority situation.



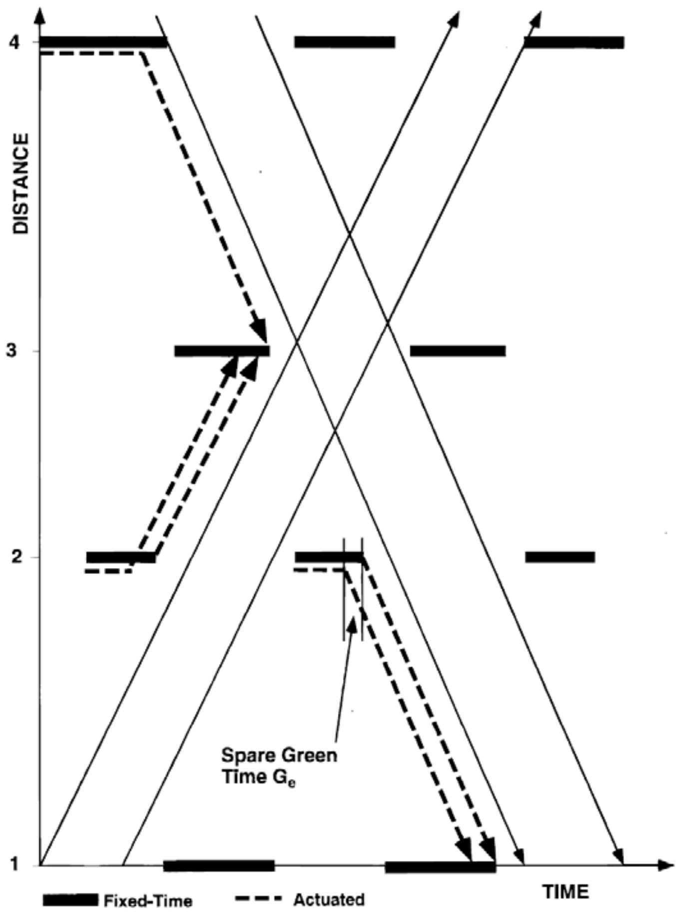
Source: Vasudevan (2005).

Figure C-5. Effect of TSP Treatment on Bus Delay

Adjusting the signal settings at the downstream intersection(s) could be difficult to be implement in offline control systems with fixed-time plans, unless buses arrive almost each cycle. In addition, it may not be appropriate to adjust the settings, because it may worsen the arterial through bandwidth, increasing the delay and number of stops for general traffic. A number of studies have proposed optimization models for active TSP considering progression of both buses and general traffic (e.g., Wa et al. 2013, Vasudevan 2005). Traffic responsive and adaptive control systems, such as SCOOT (Bretherton 1996), SCATS (Cornwell, Luk, and Negus 1986), and UTOPIA (Mauro and Di Taranto 1989) adjust the signal settings in real time to provide progressive movement to buses.

The application of optimization and simulation models requires significant cost and time resources that may be excessive for TSP planning and analysis studies prior to implementation. Simple approaches are needed for screening candidate intersections for TSP from the progression standpoint considering a pair of intersections at a time.

The problem of "wasted priority" is similar to the "early release" problem in the coordination of actuated traffic signals. Typically, the actuated phases at non-critical intersections terminate early and the spare green time becomes available to the next phases in the sequence. Usually the phase serving the arterial through traffic (sync phase) receives the spare time and starts early. This is shown as G_e in Figure C-6. The early start of the green for the sync phase may increase the delay and stops at the downstream signal(s), as shown in Figure C-6 (Skabardonis 1996). The arterial sync phase at intersections 2 and 4 starts early, and the vehicles have to stop at the downstream intersection 3. This increases delay and stops and creates the sense of uncontrolled traffic movements on the arterial.



Source: Skabardonis (1996).

Figure C-6. Effect of Early Green on Arterial Progression

One suggested approach to the "early release" problem consists of "shifting" the optimized signal offsets based on the estimated amount of total spare green time G_e from the termination of the actuated phases at each intersection (Skabardonis 1988). The spare green time is calculated based on the traffic demands, signal settings, and pedestrian presence. This approach may be also applied to the TSP "wasted progression" problem if the TSP given is phase advance (i.e., red truncation), and buses arrive and receive priority during almost every signal cycle. In this case, the offsets are shifted by the amount of the progression interval.

Simple criteria were developed to check whether the signal progression criterion is satisfied, on the basis of the type of priority provided, signal settings, and basic transit characteristics, as described below.

Consider a pair of signalized intersections along an arterial as shown in Figure C-7. The signals are coordinated with a common cycle length. Also shown is the trajectory of a bus receiving priority through phase advance (i.e., red truncation) at intersection 1. The bus stops between the two intersections (e.g., far-side of intersection 1, mid-block, or near-side of intersection 2). The following equation must be satisfied in order the bus to arrive during the green time at the downstream intersection 2:

$$O_2 \leq (O_1 - \tau) + \frac{L}{V_B} + D_B \leq O_2 + g_2 \tag{7}$$

where

O_1 = offset at the upstream intersection (seconds),

O_2 = offset at the downstream intersection (seconds),

τ = priority (e.g., red truncation) interval (seconds),

g_2 = green time at the downstream intersection (seconds),

L = distance between signals (feet),

V_B = bus running speed (feet per second) = speed in miles per hour × 1.47, and

D_B = bus delay between intersections (seconds) = sum of dwell time(s), re-entry delay(s), and acceleration/deceleration delays at stops between the two signals.

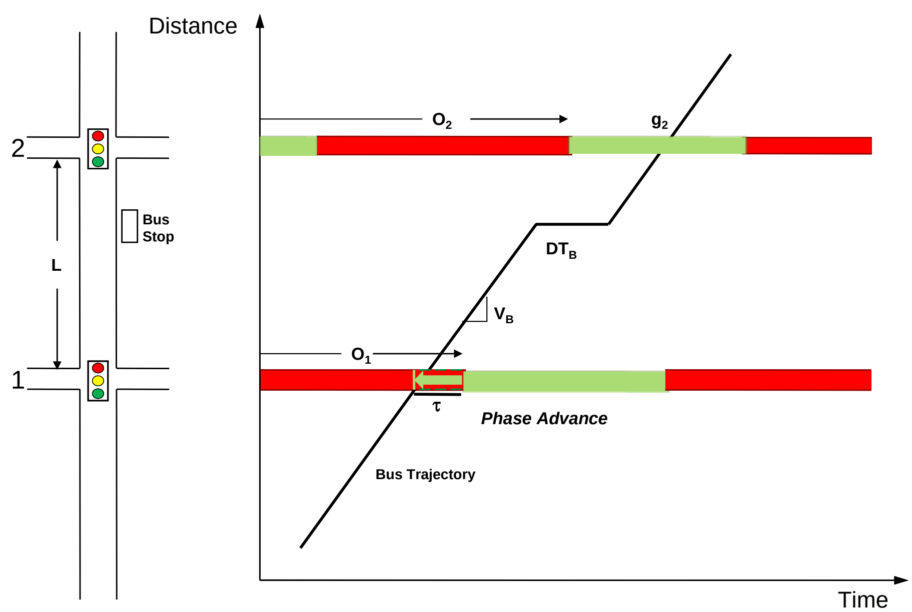


Figure C-7. Transit Vehicle Trajectory with Red Truncation

The components of bus delay—average dwell time, average re-entry delay (i.e., delay waiting for a gap in traffic when leaving the stop), and acceleration/deceleration delay—can be measured in the field or estimated using procedures given in the TCQSM (Kittelson & Associates, et al. 2013).

Figure C-8 shows the trajectory of a bus which receives priority through green extension at intersection 1. In this situation, Equation (8) must be satisfied to ensure that the bus will arrive during the green time at the downstream intersection 2:

$$O_2 \leq (O_1 + g_1 + \tau) + \frac{L}{V_B} + D_B \leq O_2 + g_2 \qquad (8)$$

where g_1 is the green time at the upstream intersection and other variables are as defined previously.

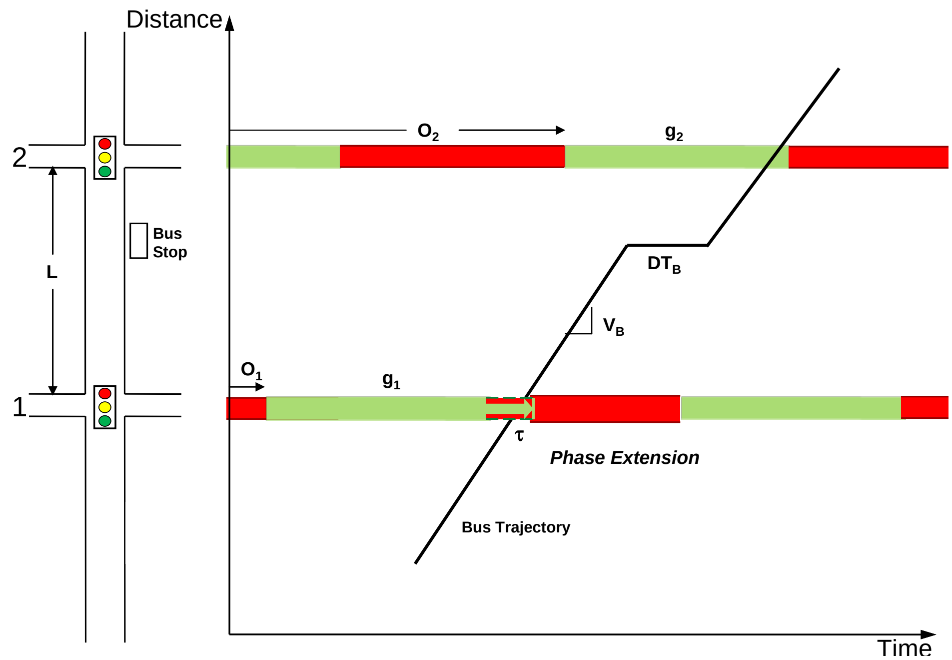


Figure C-8. Transit Vehicle Trajectory with Green Extension

The relationships given in Equations (7) and (8) provide a straightforward way to check that the priority granted at a given intersection is not "wasted". The relationships are especially useful in situations where the signal settings (offset and green times) cannot be adjusted. This situation can arise, among other reasons, because an intersection is the critical intersection in the arterial bandwidth, because two coordinated arterials meet at the intersection, or because high volumes exist on all intersection approaches.

The equations hold for undersaturated traffic conditions along the arterial, and assume there are no residual queues at the downstream intersection and all arriving vehicles discharge during the same signal cycle. Further, it is assumed there is no congestion along the arterial link to significantly affect bus speeds.

Finally, a key assumption for Equations (7) and (8) is that each bus experiences the same amount of delay (i.e., identical dwell times, identical re-entry delays) between the two signalized intersections. However, this is unlikely to be the case, except when no bus stops are provided between the two traffic signals. A rule-of-thumb given in the literature (St. Jacques and Levinson 1997, Kittelson & Associates et al. 2013) is that 95% of dwell times will be less than or equal to twice the average dwell time. Therefore, the equations indicate whether or not TSP will be wasted for a bus experiencing average delay, but do not guarantee that any given bus will be able to take advantage of the priority.

St. Jacques and Levinson (1997) described a “dwell range window” approach for estimating bus speeds that addresses a similar problem as the application of TSP—namely, will a given bus arrive at the downstream intersection during the green interval—and identified upper and lower limits for dwell time that would allow a bus to take advantage of progression. The closer the average dwell time is to the upper or lower limit, the smaller the margin for dwell time variation that would cause the bus to stop for the signal.

If data are available on a large number of individual bus dwell times at the bus stop (e.g., from AVL data), the standard deviation of dwell times can be calculated. Let m_L represent the difference between O_2 and the middle term of Equation (7) or (8). This is the available margin for the dwell time to be less than average. Similarly, let m_U represent the difference between $O_2 + g_2$ and the middle term of Equation (7) or (8). This is the upper margin for dwell time variation. Assuming that dwell times are normally distributed, statistical tables or a spreadsheet’s normal distribution function can be used to calculate the probability that a given bus’ dwell time will be shorter than average by m_L seconds. (A similar process can be used if a different dwell time distribution is assumed; the normal distribution is assumed for consistency with the TCQSM’s bus capacity model.) The probability that a given bus’ dwell time will be longer than average by m_U seconds can be similarly calculated.

For example, assume that O_2 is 70 seconds, the middle term of Equation (7) or (8) results in a value of 80 seconds, and the value of $O_2 + g_2$ is 100 seconds. Therefore, m_L is -10 seconds and m_U is +20 seconds. Furthermore, assume that the average dwell time is 30 seconds and that the standard deviation of dwell times is 60% of the average dwell time, or 18 seconds. From the normal distribution, 29% of buses will have dwell times shorter than (30-10) seconds, while 87% of buses will have dwell times shorter than (30+20) seconds. Therefore, 29% of buses would arrive before the signal turns green and would therefore receive no net benefit from TSP granted at the upstream intersection (assuming no TSP provision at the downstream intersection). Most buses, 58%, would arrive during the green interval and not have to stop and would therefore benefit from the delay savings provided by TSP at the upstream intersection. Finally 13% of buses would arrive after the signal turned red and would receive no net benefit from TSP at the upstream intersection. Therefore, considering just this pair of intersections, buses would benefit from TSP at the upstream intersection 58% of the time, while the benefit would be wasted the rest of the time, as those buses would depart the downstream intersection at the same time they would have if they had not been granted TSP at the upstream intersection.

Appendix D. Simulation Study

INTRODUCTION

This appendix describes the work performed for the Simulation Study subtask. It details the microsimulation modeling used to assess the performance of transit preferential intersection strategies.

Research Need

The use of simulation provides a low-cost alternative to implementing real-world experiments to help determine the operational effects of transit-related intersection treatments.

Research Objective

The objective of this subtask was to measure the change in intersection operational performance metrics as a result of different transit preferential strategies. The simulation model provides an experimental laboratory to incrementally adjust parameters and examine how buses and general traffic respond to those adjustments. The effort aimed to find answers to the following questions:

- Do buses benefit from a particular strategy? Under what conditions?
- How is general traffic affected by a particular strategy and what is the magnitude of the effect?
- Do the effects of strategies vary under different traffic volumes?
- Do the effects of strategies vary with different bus headways?

Fundamental Assumptions

When developing the simulation models, several fundamental assumptions were made to create the modeling environment:

- The experimental zone would be bounded by untreated intersections (i.e., the intersections at the terminal ends of the model would not be modified with any transit preferential strategies).
- All traffic signals would be modeled using the PTV RBC signal controller..
- No lane restrictions would be imposed on transit vehicles.
- Pedestrian delay would not be explicitly tracked, but the signal timing would not allow for violation of minimum pedestrian walk and clearance times.

Organization

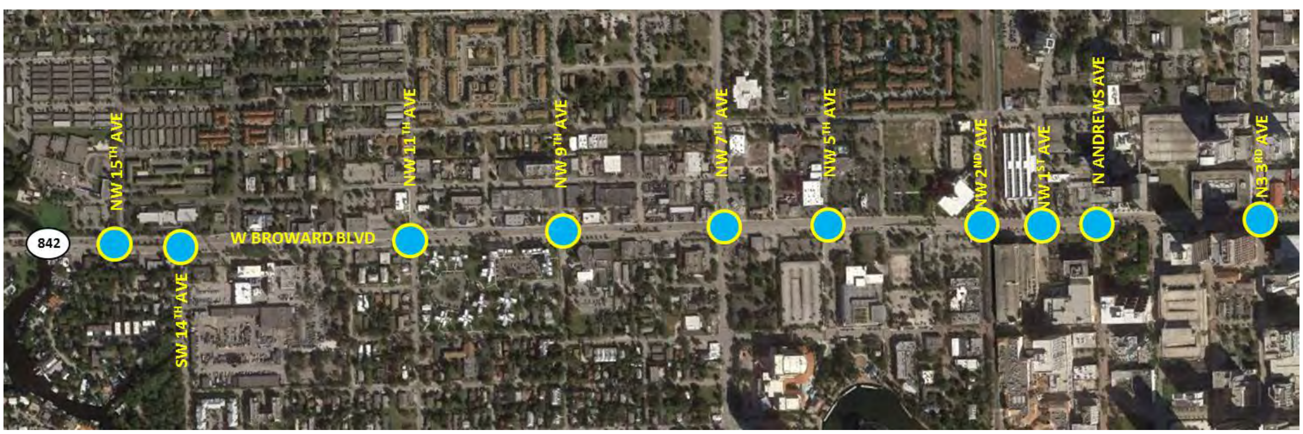
This appendix contains the following sections:

- **Modeling**, describing scenario development at the intersection and corridor levels, providing a list of variables considered in model calibration, and describing TSP operations and the simulation parameters and process.
- **Results,** presenting the findings from the intersection- and corridor-level analyses, with performance measures consisting of bus delay, non-bus delay, side street delay, bus travel time, non-bus travel time, and queuing.
- **Conclusions,** summarizing the results of the subtask.
- **Discussion,** integrating the results of this work with that of other TSP-related findings from other subtasks.

MODELING

Simulation Model

The simulation model was built and run in VISSIM 4.30-13. A calibrated model of a 1.3-mile segment of Broward Boulevard in Fort Lauderdale, Florida, previously developed by members of the research team, was used as the testbed. The extent of the modeled study area is shown in Figure D-1.



Source: © 2014 Google.

Figure D-1. Study Area

This model was chosen for its variation of congested and uncongested intersections. While this model was originally developed using real-world data (e.g., traffic volumes, traffic signal parameters), the fully developed simulations are not intended to simulate Broward Boulevard's existing or potential operations. Adjustments to volumes, driveway accesses, and lane configurations were changed as needed to create the test environment needed.

Strategies Tested

The following transit preferential strategies were tested:

- **Bus stop relocation.** Scenarios were developed to compare the effects of the stop location being near side or far side at the subject intersection.
- **Queue jump.** A queue jump provides an advance green for buses stopped in a right-turn lane. The bus is allowed to merge back into the adjacent lane before general traffic is given its green. The time for the queue jump is taken from the parallel green movement, on the order of 3–4 seconds of green time. Queue jumps are normally provided in conjunction with a near-side stop; however, a queue jump in conjunction with an on-line (i.e., bus stops in the travel lane) far-side bus stop was also tested.
- **Queue bypass.** A queue bypass allows buses to use a right-turn lane to bypass the queue stopped at a signal. When the signal turns green for the bus' approach, the bus proceeds across the intersection to an off-line far-side bus stop. In the simulation model, the right-turn lanes already existed; the change made was to add the off-line bus stop on the far side of the intersection.
- **Transit signal priority (TSP).** TSP was implemented through two primary functions: green extension and early green (i.e., red truncation). Green extension allows buses approaching the intersection towards the end of the green time to extend the green time enough to pass through the intersection. Early green provides the start of green earlier to buses waiting at a red signal. All scenarios treated with TSP included both green extension and early green functions. Details regarding the programming of this functionality are provided later.

Scenario Development

Testing the effects of the treatments listed above was conducted at two levels of analysis: intersection- and corridor-level analysis. The intersection analysis provided preliminary findings to aid in the development of the corridor-wide model.

Intersection-Level Scenarios

At the intersection level, the transit preferential strategies were applied at a single intersection, NW 7th Avenue, to identify their effects at a point location. For this level of analysis, three modeled intersections were used to isolate the treatment effects at the test intersection: NW 9th Avenue, NW 7th Avenue, and NW 5th Avenue.

NW 9th and NW 5th Avenues served as the entrances to the model and were not modified. NW 7th Avenue was selected as the subject intersection because it offered heavier side-street volumes which were suspected to experience greater impact when the various strategies were applied. Table D-1 summarizes the analysis scenarios investigated for the intersection-level analysis.

Table D-1. Intersection-Level Analysis Scenarios

Scenario	Description
Existing operations, near-side	No changes to signal timing/phasing; test stop location near-side.
Existing operations, far-side	No changes to signal timing/phasing; test stop location far-side.
Queue jump, near-side	Program queue-jump into signal timing on arterial (both directions); test stop location near-side.
Queue jump, far-side	Program queue-jump into signal timing on arterial (both directions); test stop location far-side.
Queue bypass lane	Install queue bypass lane at intersection along arterial, and locate stop far-side along bypass lane.
TSP, near-side	Program advanced signal TSP along arterial (both directions); test stop location near-side.
TSP, far-side	Program advanced signal TSP along arterial (both directions); test stop location far-side.
TSP, near-side, pedestrian recall	Program advanced signal TSP along arterial (both directions); test stop location near-side. This scenario also enables pedestrian recall on all approaches.
TSP, far-side, pedestrian recall	Program advanced signal TSP along arterial (both directions); test stop location far-side. This scenario also enables pedestrian recall on all approaches.

The scenarios described in Table D-1 served as the treatment-related differentiators between variables to test. In addition to the variation in treatments, the effects of congestion levels (three levels) and bus frequency (three levels) were also considered across all scenarios. As a result, each variation in a given treatment is tested through nine scenarios (each volume and each headway scenario), resulting in 81 scenarios.

Traffic Volumes

Understanding the effects on the various strategies at differing traffic volume levels was considered to be useful. Knowing whether strategy benefits were lost or gained at different traffic levels would help in developing guidance on whether strategies were more or less effective at certain times of day (i.e., peak or off-peak periods). To model different levels of congestion, traffic volumes were scaled proportionally to achieve the following volume-to-capacity (v/c) ratios at 7th Avenue:

- v/c = 0.50 (corresponding to a minor intersection or an off-peak period)
- v/c = 0.80 (a moderately busy intersection)
- v/c = 1.00 (a major intersection at capacity)

Findings from testing these different traffic levels were used in developing the corridor-level scenarios.

Bus Headways

Some of the tested strategies affect the intersection's signal timing and phasing. Therefore, how often these strategies are activated becomes a contributing factor to operational performance. Frequent bus headways could result in sufficiently many signal timing adjustments to create disbenefits to general traffic, bus traffic, or both. The tested headways were:

- 15 minutes (4 buses per direction per hour),
- 10 minutes (6 buses per direction per hour), and
- 5 minutes (12 buses per direction per hour).

Bus Dwell Times

To create a range of bus arrival times at the study intersection, an average dwell time of 90 seconds was used at the upstream bus stop, with a standard deviation of 50 seconds. This approach produced the side-effect of making bus travel time through the intersection study area long relative to automobiles (as the bus travel time includes dwell time at two bus stops). However, as the focus of the intersection-level analysis was to compare absolute differences in bus travel times with different strategies, this approach does not change the conclusions, and it ensures that buses arrive at the study intersection at many different times during the traffic signal cycle. At the study intersection, an average dwell time of 20 seconds was used, with a standard deviation of 15 seconds.

Corridor-Level Analysis

For the corridor-level analysis, the focus shifted from variables regarding headways and stop locations to the effects of where TSP is implemented along a corridor. Specifically, the analysis was performed with the following question in mind: *Which intersections should be treated with TSP?* Table D-2 summarizes the corridor scenarios that were developed.

Table D-2. Corridor Scenarios

Scenario	Description
Existing operations	Existing volumes, no TSP
Major intersections	TSP at major intersections, v/c ≥ 0.9
Medium intersections	TSP at medium intersections, 0.6 < v/c < 0.9
Minor intersections	TSP at minor intersections, v/c ≤ 0.6
All intersections	TSP at all intersections
All intersections, 2-minute headways	TSP at all intersections, 2-minute bus headways

Note: v/c = volume-to-capacity ratio.

The 2-minute headway scenario was modeled to see the most extreme condition where TSP would be provided at all intersections and there would always be a bus to take advantage of the TSP operation. The scenario was originally modeled as 1-minute bus headways, but caused buses to back up on each other. Using 2-minute headways allowed for increased bus frequencies without the issue of exaggerated delay and queuing at stop locations.

An average dwell time of 20 seconds was used at all bus stops in all scenarios, with a standard deviation of 15 seconds.

The only changes made to the existing signal timing were to implement signal priority measures (i.e., green extension, early green, queue jump). No offsets or force-offs were changed to optimize progression. The existing signal timing progresses eastbound traffic through the corridor (i.e., toward downtown Ft. Lauderdale) during the a.m. peak period. The traffic signal cycle length in the corridor is 160 seconds.

The model's volumes were calibrated to produce a range of v/c ratios along the corridor. Table D-3 shows the performance metrics from the original volumes to produce desired v/c ratios (as per HCM 2000 methodology). Running the simulation for 10-runs (under Existing scenario), those volumes were re-inserted into Synchro to determine the HCM 2000 results.

Table D-3. Intersection Performance for Existing Conditions Pre- and Post-Simulation Volumes

	Intersection v/c Ratio		Intersection LOS		Average Intersection Delay (seconds)			
Cross-Street	Syn-Orig	Syn-PV	Syn-Orig	Syn-PV	Syn-Orig	Syn-PV	Diff.	% Diff.
NW 15th Ave	0.80	0.79	A	B	10.0	11.7	1.7	17%
NW 14th Ave	0.90	0.84	A	A	8.8	9.0	0.2	2%
NW 11th Ave	0.60	0.62	B	A	10.8	5.8	-5.0	-46%
NW 9th Ave	0.70	0.74	A	B	4.4	10.2	5.8	132%
NW 7th Ave	1.00	0.94	D	D	54.3	48.8	-5.5	-10%
NW 5th Ave	0.40	0.56	A	A	4.1	5.9	1.8	4%
NW 2nd Ave*	0.60*	0.46*	A	A	0.1	0.1	0.0	0%
NW 1st Ave	0.50	0.50	B	B	11.5	11.5	0.0	0%
Andrews Ave	0.80	0.77	C	D	31.9	39.5	7.6	24%
NW 3rd Ave	0.90	0.85	E	D	58.7	51.3	-7.4	-13%

Notes: *NW 2nd Avenue intersection is unsignalized.
v/c = volume-to-capacity, LOS = level of service, diff. = difference.
Syn-Orig = Original Synchro results with pre-simulation volumes (HCM2000 methodology)
Syn-PV = Synchro results with post-simulation volumes over 10 runs.

The desired v/c ratios (shown under the "Syn-Orig" column in Table D-3) were achieved via the simulation. The extreme cases (v/c = 1.0 at NW 7th Avenue, and v/c = 0.4 at NW 5th Avenue) were difficult to achieve, but the final volumes are nevertheless within the range of desired v/c ratios (i.e., NW 7th Avenue still qualifies as a major intersection and NW 5th Avenue still qualifies as a minor intersection).

Signal Priority Operations

Signal priority operations can be programmed in a multitude of ways, and individual controllers will implement those operations through different algorithms. This section documents the specific programming used for queue jumps and green extension/early green timing in the model.

Queue Jump

Programming a queue jump in the RBC controller requires adjusting the ring-barrier diagram to include the "bus phase." Figure D-2 shows the ring-barrier diagrams for an intersection with and without a queue jump.

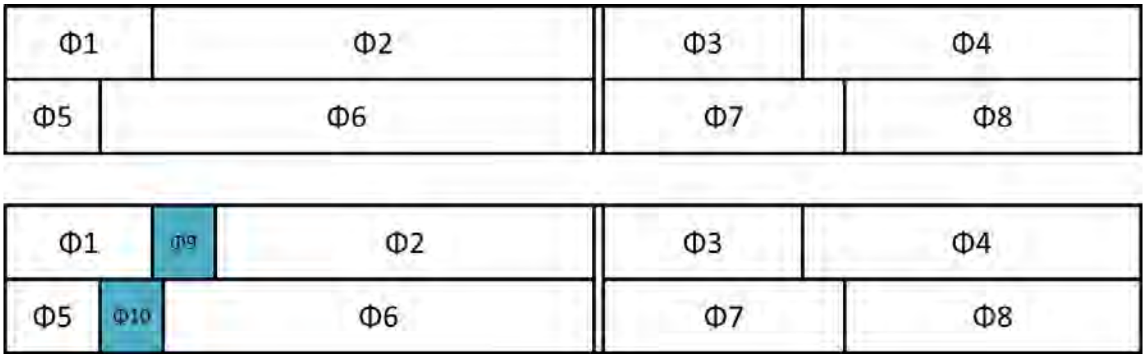


Figure D-2. Ring-Barrier Diagram Showing Typical Cycle (top) and Queue Jump Cycle (bottom)

The bus phases (Φ9 and Φ10 in Figure D-2) were placed before their parallel green movements. The phases were only activated if a bus was stopped at the intersection in the right-turn lane. The bus phases did not activate concurrently, but instead used first in/first out programming. Therefore, when a bus phase was served, all other phases were red and only buses were permitted to move (i.e., no right turns were permitted).

As the bus phase is intended to allow the bus to pull ahead of the adjacent traffic platoon, and only one bus would be expected to present at a time, the bus phase duration could be minimal. Therefore, 3 seconds of green time were provided for Φ9 and Φ10.

TSP

TSP adjusts the length of green times within the cycle to provide benefit to transit. This is done through two mechanisms: green extension and early green (i.e., red truncation). The detection method implemented was a check-in/check-out plan, which is detailed below. However, the results would be the same if a presence (continuous call) detection technology was used.

Green Extension

Green extension is a function developed for buses arriving at the signal towards the end of the green time. The extension provides the extra time needed to help the bus clear the intersection. The RBC controller codes green extension by establishing an "Extend Limit," which is the maximum number of seconds the green time will extend beyond the yield point before terminating the phase when a bus checks in with a TSP call. All scenarios were coded for a maximum of 10-second extensions.

Early Green

Early green is a function developed for buses arriving at the signal on red. The TSP request is intended to shorten phases as needed and as possible, to give the phase the bus requires a green earlier in the cycle. The RBC controller will produce an early green by truncating phases to the extent needed, without omitting phases and without violating any vehicular or pedestrian minimums. An additional set of minimums can be programmed using a "Priority Min Green" table, which can set additional minimums that exceed the global and plan minimums. This table is useful for certain phases that may require more green time than the minimum timing would permit (e.g., a heavy protected left-turn movement). For example, the northbound leg of the NW 7th Avenue intersection had a heavy left-turn movement. Without establishing a priority minimum green for this phase, side-street operations noticeably degraded.

Pedestrian Recall

Pedestrian recall is 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). Enabling the pedestrian recall function for the side street in the RBC controller has been demonstrated to affect both how the signal recovers after green extension and how it truncates phases for early green. As a result, there was a need to investigate the effects of pedestrian recall in the TSP scenarios.

Detector Plan

Setting up the detector plan for the check-in/check-out configuration is dependent on whether stops are located near side or far side. The basic premise for this configuration is as follows:

1. The bus triggers a TSP call by traveling over the “check-in” detectors upstream of the intersection, which requests TSP service on that particular approach.
2. The signal controller works to service the TSP call until the bus reaches the “check-out” detectors located past the stop bars of the approach.
3. Once a bus passes the “check out” detectors, the TSP call is dropped and the signal recovers back into coordination.

The detector plan for near-side stops is shown in Figure D-3.

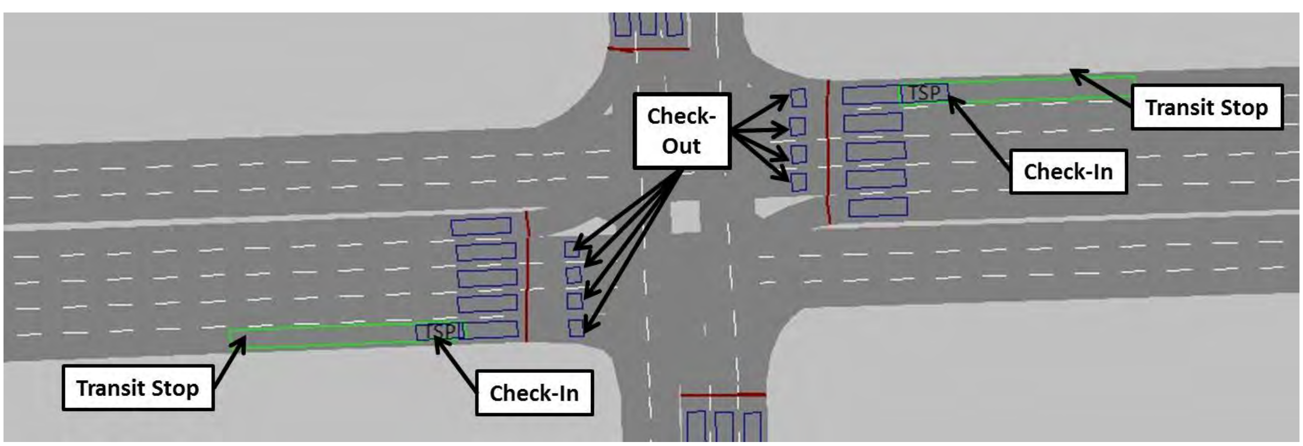


Figure D-3. Near-Side Bus Stop TSP Detector Layout

The “check-in” detectors are located at the end of the bus stop, and are only activated when the bus departs the stop (i.e., the detector is not triggered during boarding and alighting).

The detector plan for far-side stops is shown in Figure D-4.

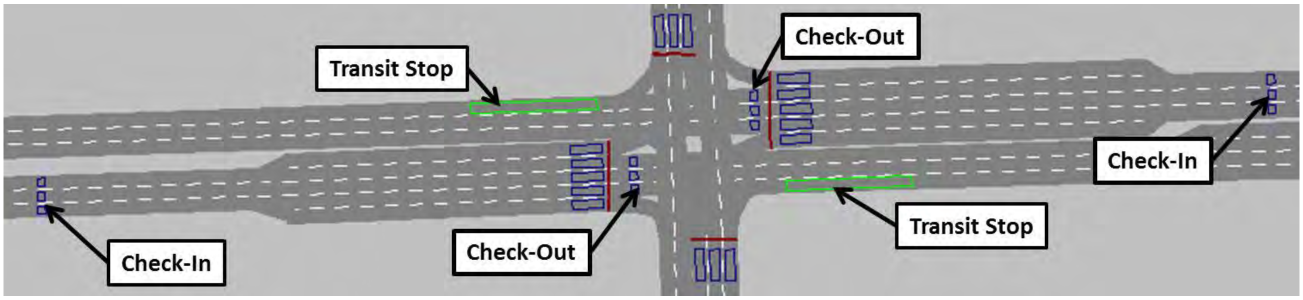


Figure D-4. Far-Side Bus Stop TSP Detector Layout

The "check-in" detectors are located upstream of the intersection, since the bus will not stop for boarding and alighting near-side. The distance upstream is determined by approximating the distance an average bus will travel during the "Extend Limit" programmed. Considering this effort used a 10-second extend limit, the distance was determined from the average travel speed of buses and this extend limit.

Simulation Process

All intersection and corridor scenarios were run 30 times each, using a unique traffic seed value for each run to produce a distribution of results. An individual scenario "run" is a total of 90 simulated minutes, broken into the following periods:

1. *15-minute warm-up period.* This period allows the model to be fully populated with traffic and for traffic signals to start up and run the expected timings.
2. *60-minute data collection period.* This is the time period where all performance measures are captured.
3. *15-minute stabilization period.* This time ensures that traffic is present continuously until the end of the data collection period.

After the runs were completed, performance metrics were analyzed for traffic during the 60-minute data collection period for all traffic, non-transit traffic, and buses individually. The collected performance metrics focused on:

- Approach delay,
- Overall intersection delay, and
- Arterial travel time.

Pedestrian delay for these analyses was not specifically analyzed. However, pedestrian delay is expected to be unaffected by the tested TSP treatments for the following reasons:

- Any geometric changes to the intersection for different scenarios did not affect pedestrians' crossing distance or path.

- No operational treatment used violated minimum pedestrian phase timing or omitted the pedestrian Walk or flashing Don't Walk intervals.
- While the MUTCD (FHWA 2009) allows for the omission of a pedestrian Walk interval as long as the associated vehicular phase is also omitted or the pedestrian phase is exclusive (see MUTCD Section 4D.27, Preemption and Priority Control of Traffic Control Signals), these options were not used. No signal timing was programed to omit any pedestrian phase and no signal timing was programed to reduce any pedestrian times.

The corridor-level analysis was modeled with real-world pedestrian volumes at intersections. These inputs were in the model to appropriately capture any additional delay to turning vehicles.

RESULTS

This section presents the findings of the intersection- and corridor-level VISSIM analyses.

Intersection-Level Results

Table D-4 presents the average travel time through the intersection for buses and for all vehicles (buses and non-buses) on the arterial approaches to the intersection. The table also shows the average intersection delay, in seconds, for all vehicles, including cross-street vehicles, under the base-case scenarios of a near-side or a far-side stop. Each scenario was tested at three levels of volume-to-capacity (v/c) ratio (0.5, 0.8, and 1.0). As noted previously, bus travel times include dwell time at two bus stops, one at the study intersection and one upstream of the study intersection, with an average dwell time of 90 seconds and standard deviation of 50 seconds used at the upstream intersection to randomize bus arrivals at the study intersection. As a result, average bus travel times through the study area appear to be much higher than for arterial vehicles generally.

Table D-4. Intersection-Level Travel Time and Delay Results (Base Case)

	Travel Time (s)		Average
Stop Location (v/c = 0.5)	**Arterial Vehicles**	**Buses**	**Intersection Delay (s)**
Near-side	39.2	181.2	24.5
Far-side	38.6	178.8	23.9
	Travel Time (s)		**Average**
Stop Location (v/c = 0.8)	**Arterial Vehicles**	**Buses**	**Intersection Delay (s)**
Near-side	43.2	187.4	31.7
Far-side	42.6	183.9	30.5
	Travel Time (s)		**Average**
Stop Location (v/c = 1.0)	**Arterial Vehicles**	**Buses**	**Intersection Delay (s)**
Near-side	49.9	199.4	41.2
Far-side	49.8	190.6	38.5

Note: v/c = volume-to-capacity ratio.

Table D-5 compares the difference in travel time and average delay for each tested strategy at each v/c level, relative to the base case of a near-side stop.

Table D-5. Intersection-Level Results, Compared to Near-Side Stop Base Case

Strategy (v/c = 0.5)	% Change in Travel Time: Arterial Vehicles	% Change in Travel Time: Buses	% Change in Average Intersection Delay
Move stop to far-side	-1.5	-1.3	-2.4
Add TSP (both directions)	-1.4	-1.5	+1.6
Add TSP (one direction)	-1.1	-1.5	+1.2
Add queue jump	+2.8	NS	+2.0
Move stop to far-side and add queue bypass	-1.8	-1.4	-2.9
Move stop to far-side and add TSP (both directions)	-2.3	-3.1	-0.8
Move stop to far-side and add TSP (one direction)	-3.3	-3.3	-1.6
Move stop to far-side and add TSP (one direction, ped recall)	+5.8	NS	-4.9
Strategy (v/c = 0.8)	**% Change in Travel Time: Arterial Vehicles**	**% Change in Travel Time: Buses**	**% Change in Average Intersection Delay**
Move stop to far-side	-1.3	-1.8	-3.8
Add TSP (both directions)	-1.4	-1.5	+3.8
Add TSP (one direction)	-2.7	-1.7	-1.9
Add queue jump	+4.9	-0.8	NS
Move stop to far-side and add queue bypass	-2.2	-2.5	-4.4
Move stop to far-side and add TSP (both directions)	-2.3	-4.1	-0.6
Move stop to far-side and add TSP (one direction)	-3.9	-4.2	-5.0
Move stop to far-side and add TSP (one direction, ped recall)	+2.8	-1.6	-13.2
Strategy (v/c = 1.0)	**% Change in Travel Time: Arterial Vehicles**	**% Change in Travel Time: Buses**	**% Change in Average Intersection Delay**
Move stop to far-side	NS	-4.6	-6.6
Add TSP (both directions)	-2.6	-4.0	NS
Add TSP (one direction)	-4.3	-5.2	NS
Add queue jump	+5.5	-3.4	+2.6
Move stop to far-side and add queue bypass	-2.2	-5.3	-8.0
Move stop to far-side and add TSP (both directions)	-2.6	-7.4	-5.8
Move stop to far-side and add TSP (one direction)	-5.5	-7.4	-5.3
Move stop to far-side and add TSP (one direction, ped recall)	+1.5	-5.3	-7.8

Notes: v/c = volume-to-capacity ratio, TSP = transit signal priority.
NS = not a statistically significant effect (alpha=0.05).

The following results can be observed from Table D-5:

- The greatest travel time benefit for both arterial vehicles resulted from the combination of moving the stop to the far side of the intersection and adding TSP in one direction only. Arterial vehicle travel times through the intersection improved by 3.3% to 5.5% (corresponding to 1–3 second reductions in travel time), while bus travel times improved 3.3% to 7.4% (corresponding to 6–15 second reductions in travel time). Overall intersection delay for all vehicles entering the intersection was reduced by 1.6% to 5.3% (0.2–2.2 seconds).
- Moving the stop from near side to far side had approximately the same impact on bus travel times as implementing TSP.

- Queue jumps, as expected, consistently increased arterial vehicle travel times (as the green time for the queue jump was taken from the arterial green time). They only produced a meaningful benefit to bus travel time at a v/c ratio of 1.0.
- Queue bypasses produced modest improvements to both arterial vehicle travel times (because buses no longer blocked the right traffic lane when a far-side bus pullout was provided) and bus travel times (because they could get through the intersection a little faster than previously by using the right-turn lane).
- The best improvements to overall intersection delay resulted from moving the bus stop to the far side, providing TSP in on direction along the arterial, and calling the cross-street pedestrian phase (thereby providing a longer cross-street green) after serving a TSP request. Although the ped recall function benefitted cross-street traffic and reduced overall intersection delay, it also diluted the travel time benefits to bus traffic and resulted in higher arterial vehicle travel times.

Compared to providing TSP in both directions, providing TSP in only one direction resulted in better travel time benefits both for buses and all arterial vehicles. Additionally, when the stop was moved to the far side, adding TSP in one direction tended to equalize the travel time benefit for buses and all vehicles.

Table D-6 compares the difference in travel time and average delay for each tested strategy at each v/c level, relative to the base case of a near-side stop.

Table D-6. Intersection-Level Results, Compared to Far-Side Stop Base Case

	% Change in Travel Time		% Change in
Strategy (v/c = 0.5)	**Arterial Vehicles**	**Buses**	**Average Intersection Delay**
Add TSP (both directions)	-0.8	-1.8	+1.7
Add TSP (one direction)	-1.8	-2.0	+0.8
Add TSP (one direction, ped recall)	+5.9	+1.3	-2.5
Add queue jump	+3.0	NS	+3.8
Add queue bypass	-0.3	NS	-0.4
	% Change in Travel Time		**% Change in**
Strategy (v/c = 0.8)	**Arterial Vehicles**	**Buses**	**Average Intersection Delay**
Add TSP (both directions)	-1.1	-2.3	+3.3
Add TSP (one direction)	-2.7	-2.4	-1.3
Add TSP (one direction, ped recall)	+2.9	+0.3	-9.8
Add queue jump	+6.6	NS	+4.6
Add queue bypass	-0.9	-0.6	-0.7
	% Change in Travel Time		**% Change in**
Strategy (v/c = 1.0)	**Arterial Vehicles**	**Buses**	**Average Intersection Delay**
Add TSP (both directions)	-2.4	-3.1	NS
Add TSP (one direction)	-5.3	-3.1	+1.2
Add TSP (one direction, ped recall)	+1.5	-0.9	-1.3
Add queue jump	+6.2	-1.0	+10.1
Add queue bypass	-2.0	-0.9	-1.6

Notes: v/c = volume-to-capacity ratio, TSP = transit signal priority.
NS = not a statistically significant effect (alpha=0.05).

The following results can be observed from Table D-6:

- When a far-side stop already existed, adding TSP improved bus travel times by 1.8% to 3.3% (3–6 seconds). Providing TSP in both directions provided similar benefits to buses as providing TSP in one direction, but reduced the all-vehicle travel time benefits by more than one-half. Overall intersection delay generally increased when TSP was added, but the maximum increase in average delay was on the order of 1 second. Providing TSP in one direction only tended to equalize the travel time benefit between non-buses and buses on the arterial.
- Queue jumps in combination with an existing far-side stop consistently increased all-vehicle travel times and overall intersection delay, and provided a statistically significant bus travel time benefit at a v/c ratio of 1.0.
- Queue bypasses produced small travel time and delay benefits for all vehicles.

Corridor-Level Results

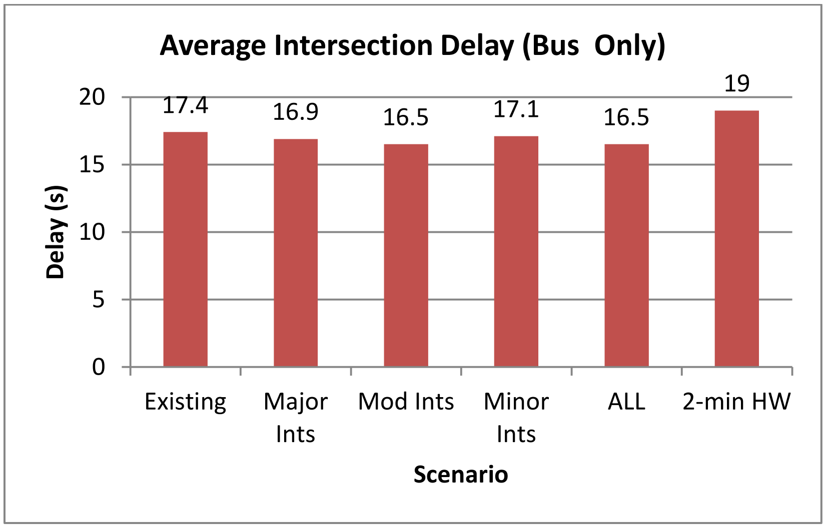
Unlike the intersection-level analysis, the overall corridor was not modeled at high, medium, and light traffic demand levels. Instead, the various intersections along the corridor were used to provide a cross section of v/c ratios. Additionally, bus headways for all corridor-level scenarios were set at 5 minutes, except for one where the headways were set at 2 minutes. This was approach was taken to model a transit-heavy corridor, and thereby analyze results from a relatively extreme situation.

Figure D-5 presents average intersection delay by scenario. For all traffic, average delay was lowest for the *Existing* and *Minor Intersections* scenarios, and was highest for the *2-minute Headway* scenario. The average intersection delay for *2-minute Headway* was 11% greater than that of the *Existing* scenario, and the average intersection delay for *Minor Intersections* was virtually equivalent to that of the *Existing* scenario. Overall, there was only a 2-second difference between the highest and lowest scenario delays.

Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-5. Average Intersection Delay by Corridor Scenario

For buses, Figure D-6 shows that the TSP implementation scenarios reduced bus delay slightly except for the extreme *2-minute Headway* scenario. The best scenarios in terms of average bus intersection delay were *Moderate Intersections* and *All Intersections*, and it should be noted that implementing TSP at just the intersections with moderate traffic demand levels resulted in the same average bus delay as the scenario with all intersections being treated with TSP.



Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-6. Average Bus Intersection Delay by Corridor Scenario

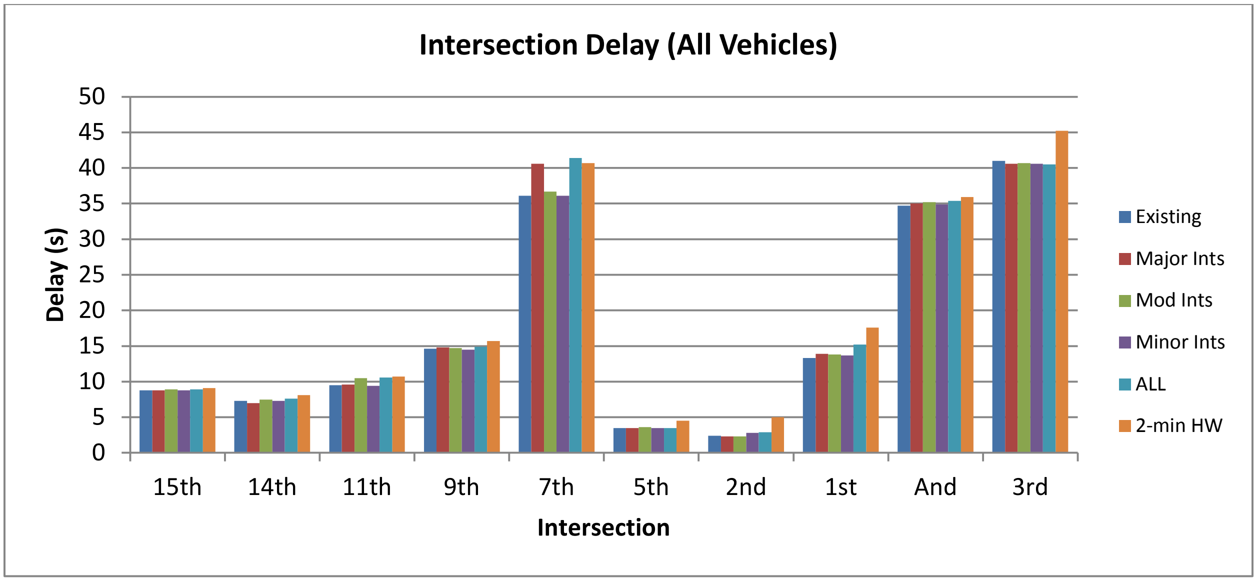
In a given scenario, TSP was implemented at an intersection on the basis of its v/c ratio for the *Existing* scenario, calculating using the HCM2000 methodology. Table D-7 shows the scenarios in which TSP was implemented by scenario. The table also indicates the bus stop location for each direction.

Table D-7. TSP Intersection Implementation by Scenario and Stop Location

Signalized Intersection	Corridor Scenario						EB Stop Location		WB Stop Location	
	Existing	Major Ints	Mod Ints	Minor Ints	ALL	2-min HW	Near Side	Far Side	Near Side	Far Side
NW 15th Ave								X[1,2]		X
NW 14th Ave		X			X	X			X[1]	
NW 11th Ave			X		X	X		X		X[1]
NW 9th Ave			X		X	X	X		X	
NW 7th Ave		X			X	X	X		X	
NW 5th Ave				X	X	X	X		X	
NW 1st Ave				X	X	X				
Andrews Ave			X		X	X		X		
NW 3rd Ave							X			X[2]

Notes: [1]Stop has bus pullout bay.
[2]Stop is modeled with a large mean dwell time and standard deviation to provide variability of bus arrival during the cycle downstream.
Ints = intersections, mod = moderate, 2-min HW = 2-minute headways, EB = eastbound, WB = westbound.

Figure D-7 shows that intersection delay did not change much from one scenario to the next at each individual intersection when all traffic was considered, except at NW 7th Avenue, which tended to drive the overall results. This is likely because NW 7th Avenue has the heaviest cross-street volumes of the study intersections.



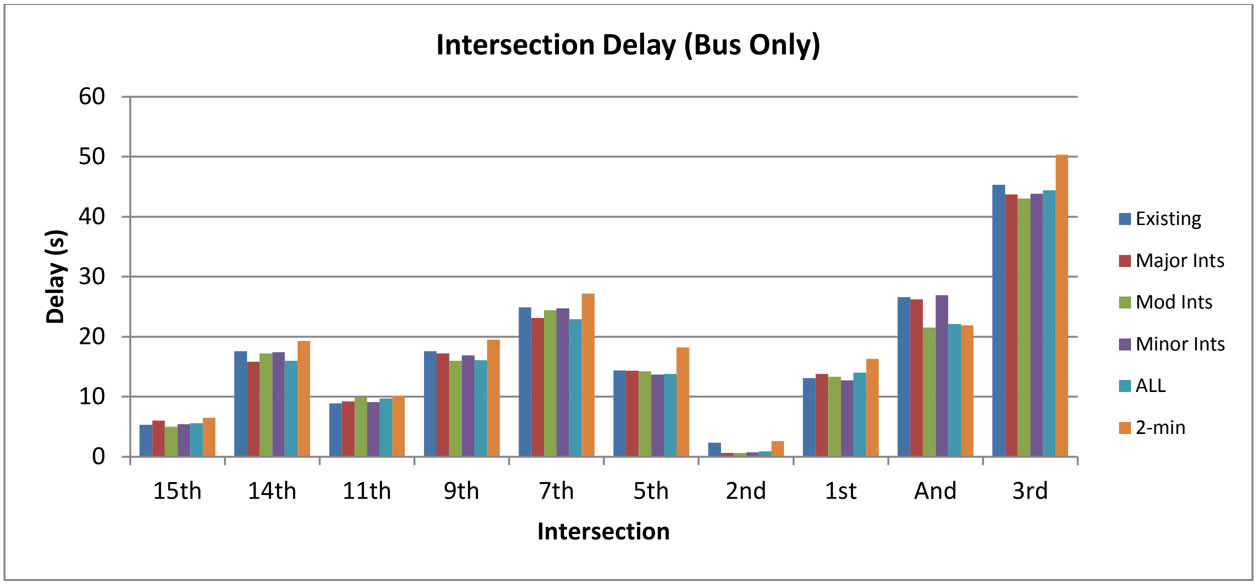
Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-7. Average Delay for All Vehicles by Intersection

Intersection delay tended to be highest at NW 7th Avenue, Andrews Ave, and NW 3rd Avenue. Intersection delays at NW 15th Avenue and NW 3rd Avenue were largely unchanged across scenarios, as expected, considering that they serve as the model termini and are untreated, except for NW 3rd Avenue under the *2-minute Headway* scenario. The increase in delay at NW 3rd Avenue appears to come from the eastbound through movement conflicting with the westbound left turn, potentially due to the increase in bus frequencies (from approximately 10–11 buses to 20–24 buses during the analysis period).

Implementing TSP at NW 7th Avenue tended to increase the overall delay at that intersection, but did not affect delay at the adjacent signalized intersections.

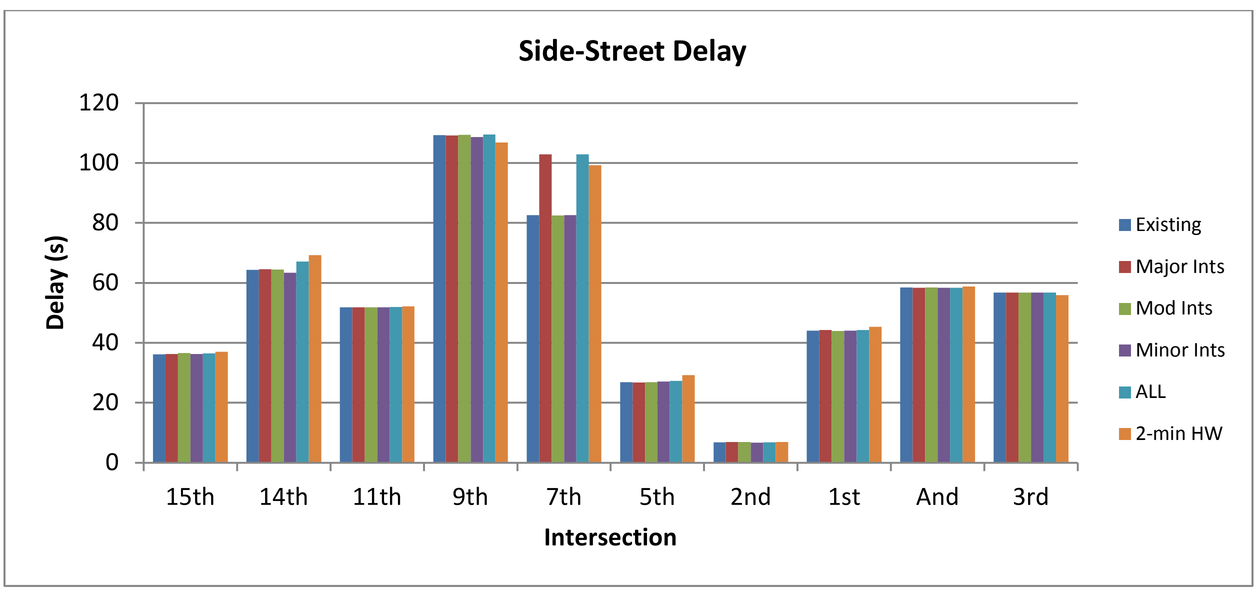
When examining bus delay at each intersection (Figure D-8), there was a noticeable increase in delay at nearly every intersection in the *2-minute Headway* scenario, and (typically) slight decreases in the other scenarios, except at Andrews Avenue. The extreme frequency of buses under the *2-minute Headway* scenario appears to be too much for the system to accommodate. In reality, there may be buses arriving too frequently at the intersections to take advantage of a cycle that can accommodate either an early green or a green extension, but not both. At 160-second cycle lengths, approximately 2.67 buses approach an intersection per cycle.



Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-8. Average Delay for Buses by Intersection

Side-street delay was notable at the major intersections (i.e., intersections with v/c ≥ 0.90), which include NW 14th Avenue and NW 11th Avenue, as shown in Figure D-9. The *Existing*, *Moderate Intersections*, and *Minor Intersections* scenarios had the lowest side-street delays, while the *Major Intersections*, *All Intersections*, and *2-minute Headway* scenarios had the highest side-street delays. This result is consistent with expectations, since the *Major Intersections*, *All Intersections*, and *2-minute Headway* scenarios implemented TSP at both the NW 7th Avenue and NW 14th Avenue intersections.

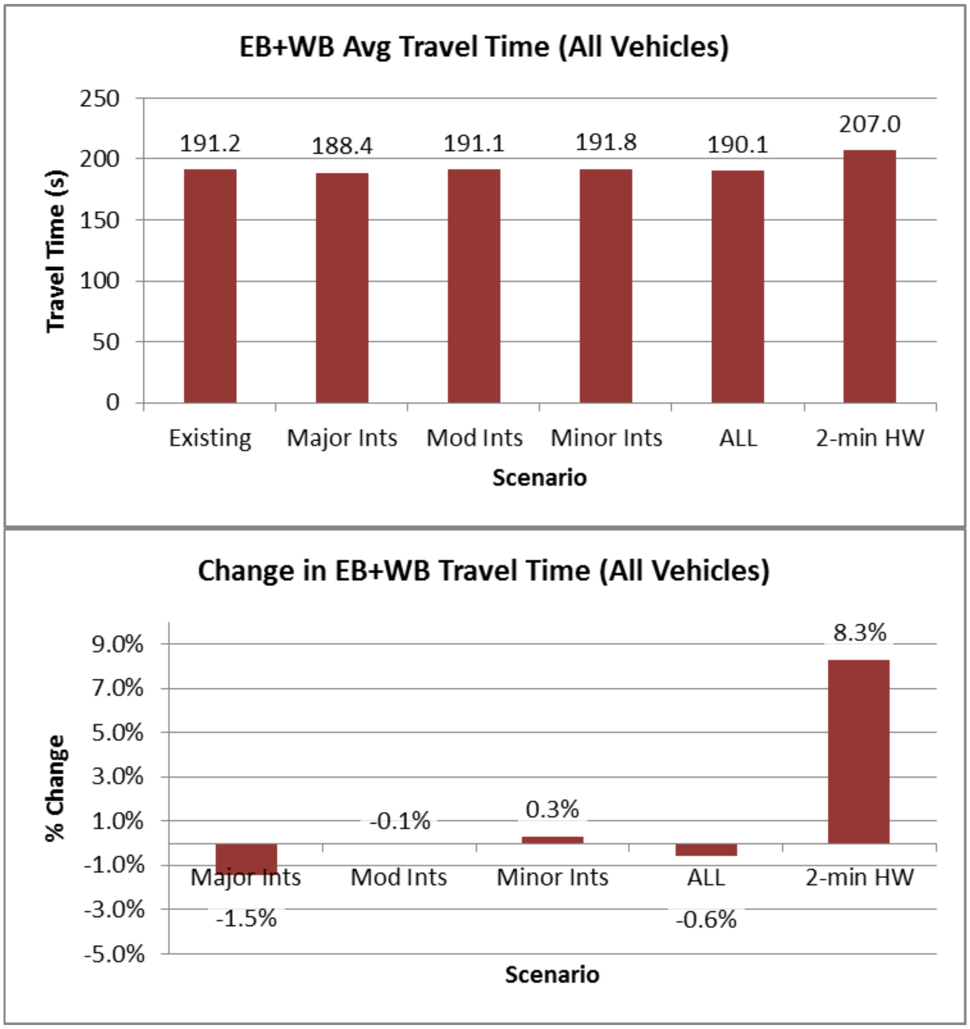


Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-9. Average Side-Street Delay by Intersection

Other than the increase in side-street delay at NW 7th Avenue and NW 14th Avenue, the implementation of TSP had minimal effect on side-street delay at any of the other intersections.

For all traffic, travel time (average of both directions) was lowest for the *Major Intersections* scenario, as shown in Figure D-10. The range in average travel times for the scenarios with 5-minute headways was 3.4 seconds; travel times for the *2-minute Headways* scenario were at least 15 seconds longer than the other scenarios.

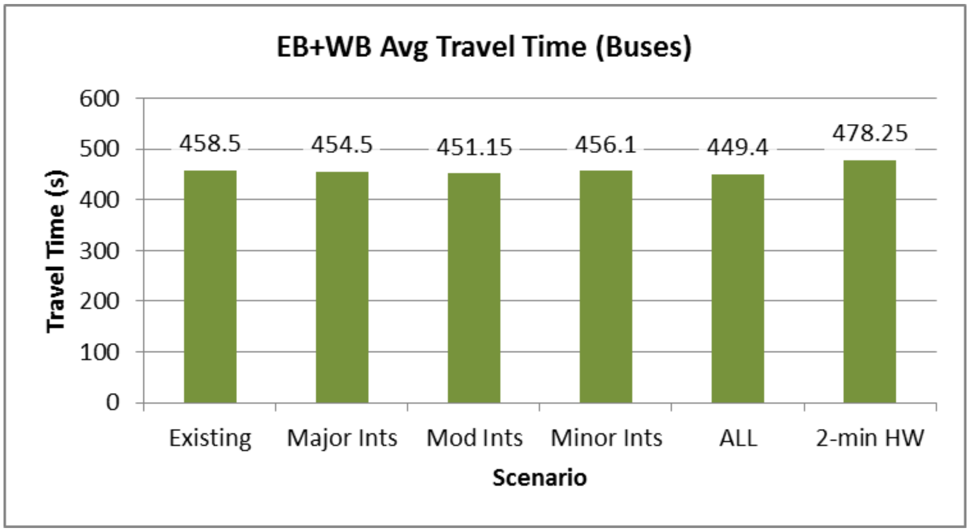


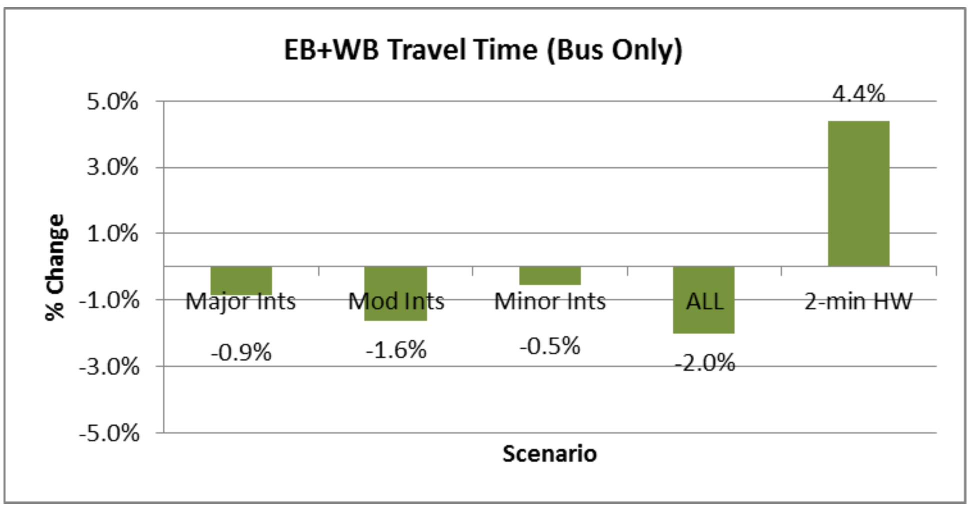
Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-10. Average Corridor Travel Time for All Vehicles

As shown in Figure D-10, when TSP was implemented at major and moderate intersections, travel time improved for all traffic. The *2-minute Headway* scenario showed an 8.3% increase in average travel time, likely due to high bus volumes increasing the blockage of curbside lanes and the bus' relatively slow speeds compared to the rest of the traffic stream.

For buses, travel time (average of both directions) was lowest for the *All Intersections* scenario and highest for the *2-min Headway* scenario, as shown in Figure D-11. However, the overall decrease in bus travel time through the corridor was relatively small, with a maximum travel time reduction of 9 seconds in the *All Intersections* scenario.

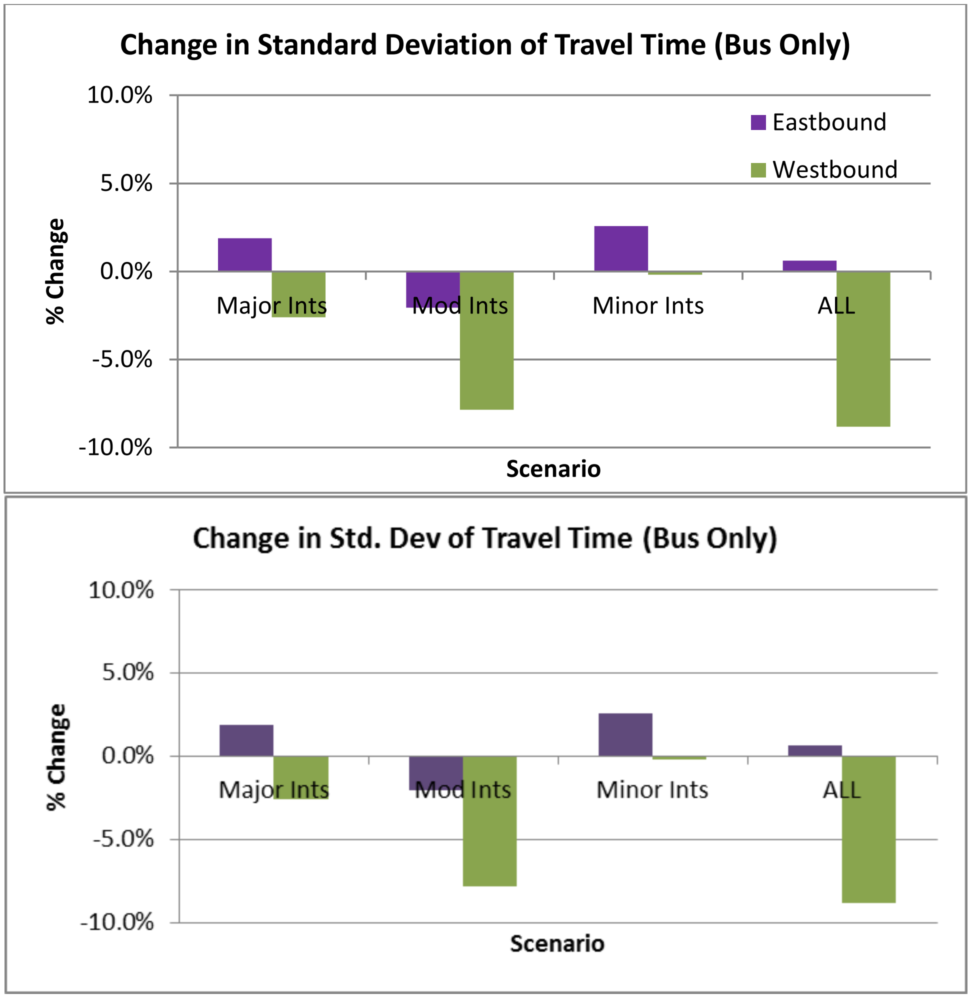




Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-11. Average Corridor Travel Time for Buses

Figure D-12 evaluates the impact of the TSP scenarios on bus travel time variability. The standard deviation of westbound bus travel times decreased approximately 8% when TSP was implemented at only the moderate-demand intersections, and decreased approximately 9% when TSP was implemented at all intersections. Implementing TSP only at the major intersections had a much smaller effect on westbound bus travel time variability, and implementing TSP only at the minor intersections had almost no effect on westbound bus travel time variability. At the same time, eastbound travel time variability increased in every scenario, except the *Moderate Intersections* scenario.



Note: Ints = intersections, mod = moderate, 2-min HW = 2-minute headways. See Table D-2 for scenario descriptions.

Figure D-12. Change in Corridor Travel Time Variability for Buses

CONCLUSIONS

The results of the simulation analysis support the following conclusions:

- Moving a stop from the near side of a signalized intersection to the far side reduced travel time through the intersection for both the buses using the stop and for parallel through traffic. The magnitude of the improvement for buses increased as traffic demands (v/c ratio) increased, but decreased for parallel traffic as the v/c ratio increased. This strategy reduced overall intersection delay, with the magnitude of the reduction increasing as the v/c ratio increased.
- Providing TSP only in one direction tended to provide better intersection travel time and delay benefits, compared to providing TSP in both directions.
- The effects of moving a bus stop from near side to far side, and the effects of providing TSP in one direction only, were approximately additive at the intersection

level (i.e., the sum of the whole was about the same as the sum of the individual strategy parts).

- Implementing pedestrian recall as part of the signal timing, in conjunction with providing TSP in one direction, tended to worsen travel time through the intersection for both buses and parallel through traffic, compared to not implementing pedestrian recall, but consistently reduced overall intersection delay.
- Implementing TSP tended to increase average intersection delay, but decrease travel times through the intersection for both buses and parallel through traffic.
- Implementing TSP at intersections with v/c ratios > 0.9 substantially increased side-street and overall intersection delay.
- The bus travel time benefit from TSP at any given intersection was relatively small. The overall corridor benefit was also small (up to 9 seconds savings over the 1.3-mile corridor length) and less than the sum of the individual intersection improvements.
- Implementing TSP only at intersections with moderate traffic demand levels (v/c ratio between 0.6 and 0.9) produced the best reduction in bus travel time variability. Implementing TSP at all intersections produced a slightly better reduction in variability in one direction, compared to implementing only at moderate-demand intersections, but worsened variability in the other direction.
- Implementing TSP at one intersection did not have a clear effect on delay at intersections immediately upstream or downstream.
- Queue jumps in combination with a near-side stop produced greater reductions in bus travel times as intersection v/c ratios increased. They increased travel times for parallel traffic and produced a non-significant or small increase in overall intersection delay.
- Queue jumps in combination with a far-side on-line stop increased bus travel time at a v/c ratio of 0.5 and slightly reduced bus travel times at higher v/c ratios, increased the travel time of parallel traffic more than with a near-side bus stop location, and increased overall intersection delay, with the magnitude increasing at higher v/c ratios.
- Queue bypasses in combination with a far-side off-line stop produced small reductions in bus travel times through the intersection, larger reductions in parallel traffic travel times, and small reductions in overall intersection delay.

DISCUSSION

The results of the simulation indicate that TSP provided little travel time benefit to buses through this corridor, but did reduce travel time variability. This result may be due to a couple of factors:

- The traffic signal timing through the corridor was already optimized, so buses may have been able to take advantage of the arterial green time and signal progression provided to arterial traffic generally without having to request a green extension very often. The intersection-level finding that providing TSP in both directions on the arterial resulted in a smaller travel time benefit than providing TSP in the peak direction only supports the hypothesis that altering the signal timing to benefit non-peak buses disbenefits peak-direction traffic (buses and non-buses), and generates a net disbenefit for arterial traffic as a whole.

- The traffic signal spacing through the corridor is relatively short (approximately 750 feet on average). Therefore, there are relatively frequent opportunities for buses to lose the delay savings achieved at one intersection at a downstream intersection. Thus, a 10-second delay reduction at one traffic signal may translate into 10 seconds of extra waiting time at the next signal, with the result that little change in overall travel times is observed.

The literature (e.g., Smith et al. 2005) reports a wide range of corridor travel time benefits as a result of TSP, as well as a tendency for greater reported travel time improvements when the arterial traffic signal timing was optimized at the same time that TSP was implemented, so the findings of the simulation are not inconsistent with some communities' experiences. The simulation results are also consistent with Albright and Figiliozzi (2012), who found that TSP effectiveness evident at the stop and intersection level can be "hidden or evened out when analyzing effectiveness at a route level, " and that it is therefore important to evaluate TSP at both a corridor/route and intersection level.

Nevertheless, the literature does provide results from a number of real-world and simulated corridors where TSP did provide both a travel time and a travel time variability benefit. Therefore, it should not be concluded from this simulation that TSP does not provide a significant travel time benefit; rather that TSP *does not always* provide a significant benefit, and it may be worthwhile to investigate lower-cost strategies first (e.g., stop relocation, traffic signal timing optimization) prior to investing in TSP.

Appendix E. Innovative Strategies

INTRODUCTION

This appendix presents the results of an investigation of the following innovative transit preferential strategies that were identified during the Phase I literature review and agency interviews:

- *Bus pre-signals,* traffic signals installed on one direction of a street in advance of a signalized intersection that are used to manage queues at the intersection and to provide priority for buses travelling in a bus lane, when conditions make it impractical to continue the bus lane all the way to the intersection.
- *Bus-only links,* short sections of roadway that can only be used by transit vehicles and other authorized vehicles (e.g., emergency vehicles) that are typically used to provide bus access between neighborhoods and into activity center areas and to allow buses to make turns prohibited to general traffic.
- *Special bus phases,* which are defined for the purposes of this appendix as traffic signal phases included in the traffic signal cycle to serve bus movements that cannot be served concurrently with other traffic, such as bus left turns from a right-side bus lane or making turns into and out of a median bus lane.
- *Traffic signal shadowing,* a technique where a bus at an unsignalized intersection triggers a call for a phase at a nearby signalized intersection; when that phase is served, a gap in traffic is created that allows the bus to complete its turn.
- *Bus boarding islands,* bus stops on raised concrete islands within the roadway, used to allow buses to stop to serve passengers in locations where providing a curbside stop would be detrimental to bus operations.

These strategies were selected for investigation, because while they have been successfully implemented internationally, there has been limited or no experience with them in the United States.

BUS PRE-SIGNALS

Description

Bus pre-signals are traffic signals installed on one direction of a street in advance of a signalized intersection. They can be used to manage queues at the intersection (keeping the *reservoir area* between the pre-signal and the intersection clear of stopped vehicles), and to provide priority for buses travelling in a bus lane, when conditions make it impractical to continue the bus lane all the way to the intersection. There are three main applications of pre-signals:

1. **Virtual bus lane.** In this application (Figure E-1), 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.

2. **Bus merge assistance.** 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. This application can also be used to assist buses in re-entering traffic from an offline bus stop, as illustrated in Figure E-2.
3. **Bus weave assistance.** 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 E-1 illustrates one possible configuration for a virtual bus lane. 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 additional 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. The pre-signal is 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.

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 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 advance area.

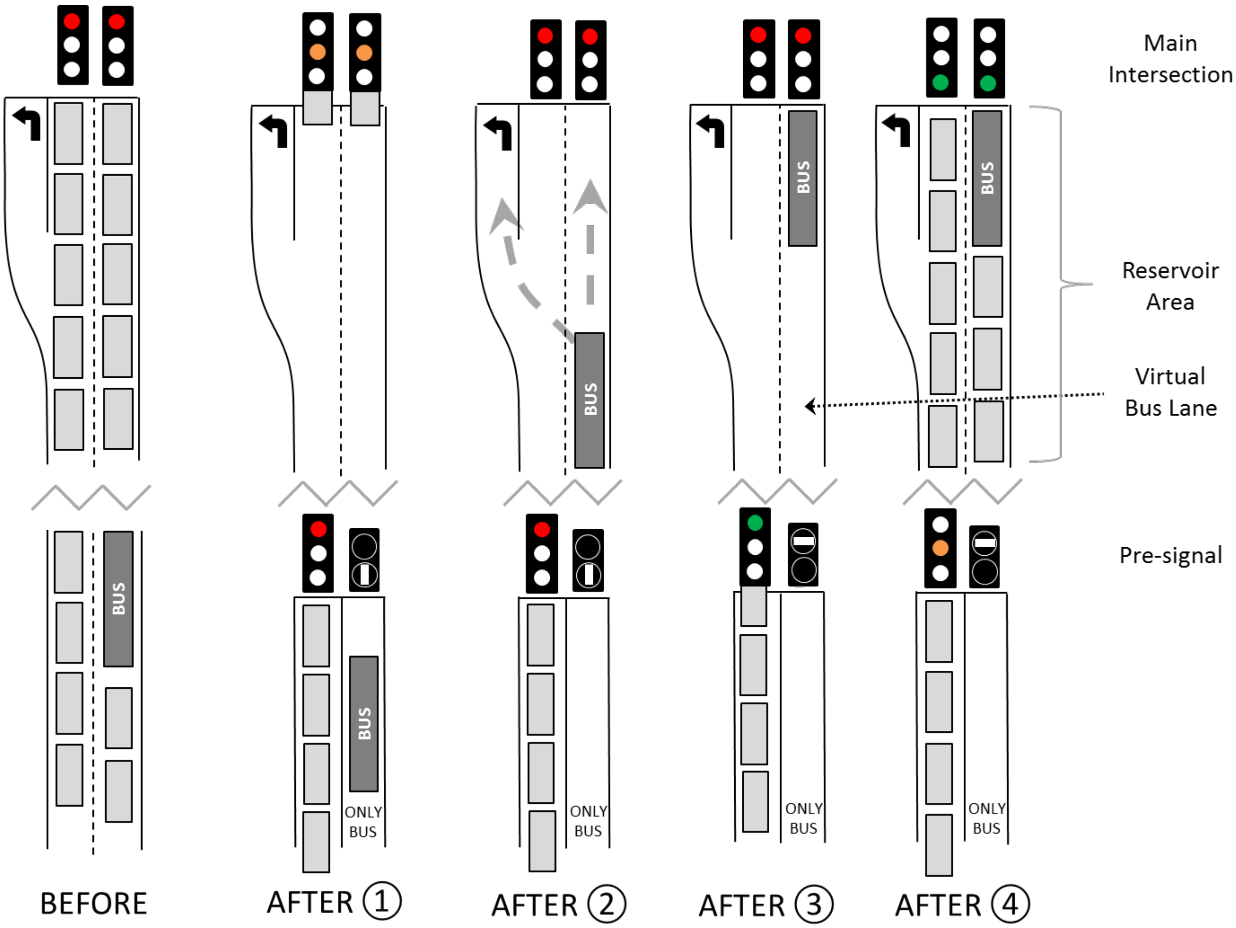


Figure E-1. Examples of Virtual Bus Lane and Weave-Assist Applications for Pre-signals

(a) Frederiksberg, Denmark

(b) Svendborg, Denmark

Figure E-2. Examples of Merge-Assist Applications for Bus Pre-Signals

Figure E-2 illustrates two pre-signal merge-assistance applications in Denmark. In photo (a), a short bus lane ends at a mid-block bus stop, and the right-of-way is used for a right-turn lane (prior to the intersection) and a bicycle facility (past the intersection). The pre-signal provides a gap for buses to merge into the general-purpose lane after serving the bus stop. The number of general-purpose lanes is the same before and after the pre-signal. In photo (b), a pre-signal is used to provide a gap in traffic to assist buses when exiting a transit center adjacent to the roadway. In both cases, a regular traffic signal controls general traffic and a transit signal controls bus traffic.

Implementations

London, U.K.

London has had considerable experience with bus advance areas. London Transport Buses (Beswick 1999) studied the operation of 21 pre-signals that had been installed by mid-1998 and which were not being affected by construction activity at the time of the study. The installations were categorized as follows:

- *Constant width* (4 sites), where the bus lane changed into a general purpose lane downstream of the signal; buses had free-flow operation at two sites and had were controlled by bus signals at the other two sites;
- *Bus lane continues* (5 sites), where the bus lane continued past the pre-signal to the main intersection and was controlled by bus signals at the main intersection; and
- *Wider upstream* (12 sites), where buses had to merge into the adjacent lane after the pre-signal; buses had free-flow operation at two sites, had to yield to other traffic at two sites, and were controlled by bus signals at eight sites.

All of the studied installations were considered to operate satisfactorily, except for the two constant width sites with free-flow operation. One site experienced crashes, where a raised island separated the bus lane from the general-purpose lane; the other site was located past the critical intersection and thus did not provide a significant delay-reduction benefit.

The study resulted in the following recommendations:

- Pre-signals could be installed immediately upstream of the intersection that constrains a roadway's capacity.
- The signal timing should (1) allow the area between the pre-signal and the intersection to fully empty during the approach's green phase and (2) allow buses to travel through the main intersection on the next green phase after arriving at the pre-signal.
- Pre-signals should operate full time, unless there are overriding reasons not to do so.
- Road markings and signing should indicate which lane is reserved for buses.
- The bus lane could be signaled when there are possible pedestrian conflicts or when buses need to weave across the general-purpose lane(s) to access a turn lane.

- Bus detection should usually be employed to maximize bus priority.
- Taxis should not be allowed to use the bus lane at a pre-signal.
- Bicycles should be served elsewhere (for example, a short section of shared-use path), when there is inadequate width for both buses and bicycles.

Koumara, Hounsell, and Cherrett (2007) simulated the operation of two types of pre-signals that had been installed in London's suburbs. The first was a virtual bus lane application on an over-capacity approach to an intersection, with the difference that the pre-signal granted an immediate green to buses when they arrived (i.e., pre-emption). This operation meant the approach's green time at the main intersection was not necessarily fully utilized, as buses were allowed to proceed during times when general traffic would normally be filling the area between the pre-signal and the main signal. This operation resulted in an average savings of 11 seconds per bus, compared to a scenario where the pre-signal was turned off, but an average increase of delay of 107 seconds per vehicle in the general-purpose lane. There was a net benefit on a person-delay basis.

The second simulated pre-signal was a bus weaving application. Two scenarios were studied: a fixed-time operation similar to that illustrated in Figure E-1 (i.e., where the bus phase was served regardless of whether or not a bus was present), and an actuated operation where the bus phase was served immediately at the pre-signal, but only if a bus was present. The fixed-time operation resulted in an average savings of 1.5 seconds per bus and an average delay of 5 seconds per general-purpose vehicle. The actuated operation resulted in an average savings of 9.5 seconds per bus and an average delay of 1.5 seconds per general-purpose vehicle. Both scenarios produced a net benefit on a person-delay basis.

York, U.K.

Hodge, Jackson, and Austin (2009) studied the operation of a pre-signal in York, with the objective of optimizing the times when the pre-signal was in operation, while avoiding situations where the signal might turn off and turn back on in quick succession, due to variations in traffic flow. They recommend the following algorithm: activate when three consecutive 5-minute vehicle counts equal or exceed the activation threshold (68 vehicles per 5 minutes at the study site), and deactivate when the arrival rate is less than the departure rate and three consecutive 5-minute vehicle counts fall below the activation threshold. Using three consecutive counts helps mitigate the effects of traffic fluctuations and ensures that at least 15 minutes elapse between turning the pre-signal on and turning it off again (or vice versa). Comparing arrival and departure rates ensures that any existing queue is clearing before the pre-signal is turned off. The authors also noted a previous study found the bus lane and pre-signal combination on the study road saved buses 4–12 minutes per trip during peak periods.

Zurich, Switzerland

Guler and Menendez (2013) studied the operation of an existing pre-signal in Zurich. This pre-signal provides a virtual bus lane at a point where the bus lane must end due to right-of-way constraints, with buses merging into the general-purpose traffic lane. At this site, buses are always given priority at the pre-signal, regardless of where the main traffic signal is at in its cycle. As a result, the approach's green time may not be fully utilized during cycles when a bus arrives. The authors found this operation saved buses 8.5 seconds on average, compared to general traffic travel times when buses were not present, but increased general traffic delay by 52 seconds on average during the 19% of phases when buses were served (i.e., average delay for all general traffic during an hour increased by about 10 seconds).

Guler and Menendez (2014) used vehicle queuing theory to compare the operation of the Zurich pre-signal to scenarios where (1) a physical bus lane was continued all the way to the main intersection and no pre-signal was used and (2) all lanes were open to general traffic (i.e., mixed use). They found pre-signals always outperformed the physical bus lane at the main intersection in terms of overall person delay, but that giving unconditional priority to buses at the pre-signal reduced the capacity of the approach at the main intersection by 14%. They also found, compared to mixed-use operation in all lanes, that pre-signals reduced overall person delay when peak demand was 105% or more of capacity and off-peak demand was 85% or less of capacity. When demand was close to capacity, mixed-use lanes performed better from an overall delay standpoint, but the pre-signal still provided a bus delay and reliability benefit.

Other Locations

Other locations where pre-signals have been documented in the literature include Manchester, U.K. (Greater Manchester Public Transport Authority 2007); Melbourne, Australia (Luk, Su, and Green 2008); Brisbane, Australia and Wellington, New Zealand (Brown and Paling 2014); and Lyngby, Denmark (Trafikselskabet Movia 2011).

Existing Implementation Guidance

United States

AASHTO Transit Guide

The AASHTO Transit Guide (2014) describes the weave-assist application of a pre-signal as an "advance stop bar for bus left turns" (Section 5.5.7.5). The application described in the guide consists of a bus lane ending at a bus stop in advance of an intersection, where the bus route turns left at the intersection and it is desired to locate the bus stop prior to the bus making the turn. The pre-signal would be activated upon the bus' departure from the stop, through an in-pavement loop or other means of detection, stopping parallel traffic for a few seconds to allow the bus to weave across the traffic lanes. The pre-signal should use regular traffic signal heads for the general traffic lanes and transit signals for the bus lane, and the signals should be located far enough from the intersection that motorists do not confuse the two signal heads. "The warrant for implementing…should be based on a benefit–cost analysis, considering transit delays, safety issues, passenger transfer impacts, and net delay to general traffic."

MUTCD

The MUTCD (FHWA 2009) discusses pre-signals in a railroad crossing context in Section 8C.09. Sections of the text that have potential relevance in a transit context include:

> *Guidance:*
> 13 *Consideration should be given to using visibility-limited signal faces (see definition in Section 1A.13) at the intersection for the downstream signal faces that control the approach that is equipped with pre-signals.*
>
> Option:
> 14 The pre-signal phase sequencing may be timed with an offset from the downstream signalized intersection such that the railroad track area and the area between the railroad track and the downstream signalized intersection is generally kept clear of stopped highway vehicles.
>
> **Standard:**
> 15 **If a pre-signal is installed at an interconnected highway-rail grade crossing near a signalized intersection, a STOP HERE ON RED (R10-6) sign shall be installed near the pre-signal or at the stop line if used….**
>
> Option:
> 16 At locations where a highway-rail grade crossing is located more than 50 feet (or more than 75 feet for a highway regularly used by multi-unit highway vehicles) from an intersection controlled by a traffic control signal, a pre-signal may be used if an engineering study determines a need.

The use of traffic signals to provide priority to transit operations is addressed in Section 4D.27:

> Option:
> 07 Preemption or priority control of traffic control signals may also be a means of assigning priority right-of-way to specified classes of vehicles at certain non-intersection locations such as on approaches to one-lane bridges and tunnels, movable bridges, highway maintenance and construction activities, metered freeway entrance ramps, and transit operations.

The use of light rail transit (LRT) signals (e.g., vertical and horizontal bar signals) to control bus movements is also addressed in Section 4D.27:

> Option:
> 18 If engineering judgment indicates that light rail transit signal indications would reduce road user confusion that might otherwise occur if standard traffic signal indications were used to control these movements, light rail transit signal indications complying with Section 8C.11 and as illustrated in Figure 8C-3 may be used for preemption or priority control of the following exclusive movements at signalized intersections:
>
> A. Public transit buses in “queue jumper” lanes, and
> B. Bus rapid transit in semi-exclusive or mixed-use alignments.

Section 8C.11 provides the following guidance on the use of LRT signals:

> *Guidance:*
> 08 *LRT signal faces should be separated vertically or horizontally from the nearest highway traffic signal face for the same approach by at least 3 feet.*

Conversations with the FHWA staff person responsible for the traffic signals material in the MUTCD indicate FHWA would not require a request for experimentation to use bus pre-signals, and that the bus lane would desirably be controlled by LRT signals.

Australia

Austroads (Luk, Su, and Green 2008) identifies bus pre-signals as a potential preferential treatment. It suggests locating pre-signals one cycle length away from the intersection (e.g., "at a cycle length of 60 s and a bus speed of 15 km/h, the distance is 250 m").

Discussion

Overview

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 through 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 do so at the traffic signal. The virtual bus lane and merge-assist applications of pre-signals addresses 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.

Pre-Signal Location and Timing Considerations

Virtual Bus Lane Applications

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 such 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, as there will simply be some empty space between the pre-signal and the back-of-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 be delivering fewer vehicles to the main intersection than can be served at the intersection toward the end of the approach's green interval.

Merge-Assist Applications

Because the number of general-purpose lanes at the pre-signal and the main intersection is the same (i.e., no potential loss of efficiency due to the addition of a general-purpose lane beyond the pre-signal), the pre-signal location is more flexible than in a virtual bus lane application. The pre-signal timing should progress vehicles through to the main intersection without forcing traffic to stop twice.

Weave-Assist Applications

In a weave-assist application, the number of general-purpose lanes downstream of the pre-signal may be greater than 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 a merge-assist application, with the additional consideration that buses will need sufficient roadway space to weave over to the left-turn lane.

General Placement Consideration

The MUTCD prohibits half-signals at intersections, so pre-signals should not be placed at an unsignalized intersection or within 100 feet of one.

Queue Management Considerations

The location of the pre-signal and the expected back-of-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* (TRB 2003) 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, and 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 in the international literature, evaluating the potential for jaywalking at a location being considered for a pre-signal may result in possible countermeasures being identified, such as NO PEDESTRIAN CROSSING signage, landscaping, or railings.

Bicycle Considerations

The same considerations 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 such time the MUTCD is updated); or
- Directing bicycles from the roadway onto a short section of bicycle track or shared-use path that bypasses the signal. This is likely the only feasible option for shared bus/bike lane operation, as 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, signage exempting bicycles from the traffic signal indications would be inconsistent with the meaning of traffic signal indications provided in the MUTCD.

Traffic Signal Priority (TSP) Considerations

In many of the installations documented in the literature, pre-signals have been combined with forms of TSP both at the pre-signal and at the intersection. Typically in these installations, the pre-signal has stopped general traffic as soon an approaching bus is detected (i.e., preemption of the pre-signal), allowing the bus to proceed without stopping, and red truncation or green extension, as appropriate, has been employed at the downstream intersection to minimize bus delay. The use of TSP in these instances has been shown internationally to have a net person-delay benefit, but studies (e.g., Koumara, Hounsell, and Cherrett 2007, Guler and Menendez 2013) have also shown that significant delays (e.g., 1–2 minutes) occur to motorists during the traffic signal cycles when buses arrive, as the pre-signal delivers traffic to the intersection less efficiently in this form of operation. Therefore, whether TSP is implemented in conjunction with pre-signals will involve policy decisions on the degree to which bus movements are to be prioritized.

Stakeholders

Potential stakeholders for pre-signals include the following:

- All stakeholders normally involved with the development of a bus lane.
- Traffic signal engineers from the appropriate roadway jurisdiction.

- Lawmakers, if laws need to be changed to permit transit signals, establish fines for violations of transit signals or bus lanes, or to allow photo or video enforcement of transit signals or bus lanes.
- Law enforcement, particularly if this will be the first application of transit signals in an area.
- Bicycle advocacy groups.

Recommendations

General Recommendations

- The presence of a bus lane is a prerequisite for considering a pre-signal.
- Operate pre-signals full time.
- Use a transit (i.e., vertical and horizontal bar) signal to control bus traffic and regular traffic signal heads to control general traffic.
- Consider the need for visibility-limited signal faces at the downstream intersection.
- In a virtual bus lane application, to achieve maximum efficiency, install pre-signals at a distance (or farther) from the intersection where the reservoir area between the pre-signal and the intersection can be filled with all the vehicles that can be served in the approach's green interval.
- Pre-signals—similar to other types of traffic signals—should not be installed at, or within 100 feet of, an unsignalized intersection, per the MUTCD.
- If warranted by pedestrian crossing volumes, pre-signals can be installed in conjunction with a signalized midblock pedestrian crossing.
- To obtain maximum benefit for buses, locate bus stops either immediately prior to the pre-signal or on the far side of the intersection.
- Pre-signals can be combined with TSP treatments, but doing so makes the intersection approach operate less efficiently for general traffic.
- To avoid the need to stop bicycle traffic using the roadway, bicycle traffic can be diverted around a pre-signal or, when local conditions permit, a bicycle signal can be used to control bicycle traffic in an exclusive bicycle facility.
- Consider the possibility of pedestrian jaywalking at the pre-signal and the potential need for countermeasures.
- Consider the extent of queuing from the pre-signal and the possibility that driveways or upstream intersections could be blocked.
- The recommendations generally applying to bus lanes also apply to pre-signals.

Virtual Bus Lane Applications

- Pre-signals providing a virtual bus lane are well-suited for the critical intersection(s) along a bus facility, where as many roadway lanes as possible are needed to serve through traffic. These are the intersections with the highest volume-to-capacity ratios.

- It is frequently not necessary to continue the bus lane past the critical intersection, as the intersection limits the amount of traffic that can enter the next block, and bus operation in mixed traffic downstream of the intersection may operate without problems.
- If the bus lane is restarted downstream from the intersection, the right lane will operate as an auxiliary through lane and will likely not be fully utilized. *NCHRP Report 707* (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 operations needs (e.g., providing a right-turn lane at the next intersection) dictate ending a bus lane; or
- Buses have difficulty re-entering traffic from a mid-block stop.

Weave-Assist Applications

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

BUS-ONLY LINKS

Description

Bus-only links are short sections of roadway that can only be used by transit vehicles and other authorized vehicles (e.g., emergency vehicles). They are typically used in the following situations:

- Providing bus access between neighborhoods with limited street connectivity,
- Allowing buses to make turns that are prohibited to general traffic, and
- Giving transit vehicles to activity center areas (e.g., city centers, university campus areas) where private vehicles are restricted.

There are several ways that bus-only links (also known as *bus gates, bus-only crossings,* and *bus sluices*) can be enforced:

- **Signs and pavement markings only.** In these applications, signs or a combination of signs and pavement markings prohibit general traffic, but exempt transit vehicles. Figure E-3 shows two examples. The Portland photo illustrates a bus-only left-turn lane at a traffic signal. NO LEFT TURN EXCEPT BUS signage and BUS ONLY pavement markings are used to indicate the lane's bus-only status; the left-turn signal head is also offset from its normal position facing the left-turn lane, to make the lane appear less like a normal left-turn lane. The Sorø photo illustrates a portion of a traffic-managed neighborhood in Denmark. The circular sign prohibits all traffic, while the plaque under the sign indicates that the prohibition applies to through traffic and that buses are excepted.

- **Gates.** A variety of gates 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). A selection are shown in Figure E-4. The photo from the Hague shows gates that swing aside to allow trams and buses into a portion of the city center where cars are restricted; video enforcement is also used. The London photo shows a parking lot–style gate that raises to allow buses to access a contraflow bus lane. The Sorø photo shows a parking lot–style gate used to allow buses, but not car traffic, to travel between two subdivisions. The Copenhagen photo shows bollards that lower into the roadway when an authorized vehicle is detected; general traffic must use a circuitous route to access areas on the other side of the gate. In all of these cases signs, markings, or both warn motorists that the link is closed to general traffic; the London and Copenhagen installations also use traffic signals.

(a) Bus-only left turn (Portland, Oregon)

(b) Neighborhood access (Sorø, Denmark)

Figure E-3. Examples of Signage- and Marking-Only Treatments for Bus-Only Links

(a) Swinging gate (The Hague)

(b) Raising gate (London)

(c) Raising gate (Sorø, Denmark)

(d) Lowering bollards (Copenhagen)

Figure E-4. Examples of Gate-Type Treatments for Bus-Only Links

- **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 in the past 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 (FHWA 1980). Figure E-5 shows installations in Canada and The Netherlands.
- **Photo enforcement.** If local laws permit, photo enforcement is an option for controlling bus-only links without resorting to barrier treatments.

(a) Calgary

(b) Delft, The Netherlands

Figure E-5. Examples of Trap-Type Treatments for Bus-Only Links

Implementations

Calgary, Canada

Calgary uses bus-only links to provide transit and emergency vehicle access between adjacent subdivisions that have no public street connection (Calgary Transit 2014). They are typically installed when a new subdivision is developed adjacent to an existing one. These links allow transit service to penetrate neighborhoods that would otherwise be infeasible to serve, given the circuitous routings that would be necessary, and also improve emergency access.

Early links used a pit-type trap to prevent through vehicle traffic, supplemented by several warning signs. 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 use only 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 staff indicate they experience maintenance issues with their sliding gates, along with occasional vandalism and problems with bus drivers not stopping in the correct location to activate the gate using a remote control. When a problem occurs, maintenance staff will investigate immediately. If the problem cannot be immediately fixed, the gate will be left in an open position. Problems with the communications equipment are referred to the contractor. Each sliding gate costs about 30,000 Canadian dollars to purchase and install, and incurs approximately 8,000 to 10,000 dollars in annual operating costs. At one location with a pit-type trap, they experience at least one stuck vehicle per month that has ignored the warning signs and tried to drive across the pit. Authorized users of the bus-only links consist of Calgary Transit buses and paratransit vehicles, school buses, fire trucks, police vehicles, and ambulances; all are equipped with a remote control similar to a garage door opener.

Ottawa, Canada

Ottawa 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

Portland 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 (Figure E-3) provides a direct routing for buses at a complex intersection where there is insufficient capacity to directly serve automobile left turns.

Denmark

A variety of bus-only links have been used in Copenhagen and its suburbs, including signs and markings only, sinking bollards, and pit-type traps. As of 2010, at least 18 such links had been installed around Copenhagen (Trafikselskabet Movia 2011). The reasons for installing them included:

- Neighborhood traffic calming programs that closed cut-through routes to automobile traffic, but maintained connections for buses;
- Providing bus access into neighborhoods from major roadways, while preventing automobile access; and
- De-prioritizing automobile traffic on a major access route to the city center, in favor of improved bus operations, wider bicycle facilities, and wider sidewalks.

The pit-type traps are designed with a ramped entry, allowing motorists to extricate themselves from the trap without assistance and are signed with the equivalent of DO NOT ENTER EXCEPT BUS (Trafikselskabet Movia 2011).

The sinking bollard treatment was placed on a street providing the only direct connection to Copenhagen's new opera house and a naval base, as a means of eliminating non-local traffic from the portion of the street south of the gate, while preserving bus transit access. A signage-only treatment was installed first, but had a violation rate that was considered too high. The replacement sinking bollard treatment included traffic lights, advance signage warning of the street closure, and signage at the last public street intersection prior to the gate indicating that the street was closed beyond that point to all motor vehicles except authorized vehicles. Buses and other authorized vehicles could activate the gate to lower the bollards (Municipality of Copenhagen 2012). In September 2014, a final decision was made to remove the bus gate, as the municipality has determined the street is now needed to serve traffic from redevelopment in the area north of the gate.

The community of Sorø (population 8,000), located approximately 50 miles west of Copenhagen, has at least two bus-only links, one with signs only (on a street where through traffic is not desired, see Figure E-3) and one with a parking lot lot–style gate on a link connecting two adjacent neighborhoods (see Figure E-4).

Other Locations

Figure E-4 provides examples of gate treatments used in London and The Hague, while Figure E-5 illustrates a pit trap used in Delft, The Netherlands. U.K. Department for Transport (2004) describes several British implementations, while Griffin et al. (2005) provide additional European examples of different types of gate treatments.

Existing Implementation Guidance

AASHTO Transit Guide

The AASHTO transit guide (2014) discusses bus-only links (Section 5.5.7.1) and bus-only turns and turn lanes (Sections 5.3.2.2 and 5.5.7.3). It recommends "normal practice" should be used in the design of the link and the signage should clearly indicate the link is for authorized vehicles only. If there is a risk of a high violation rate, the guide suggests (1) additional and larger signage, (2) traffic signal control, (3) physically gating the roadway, or (4) photo or video enforcement.

MUTCD

The MUTCD (FHWA 2009) does not provide standard signs or plaques that exempt buses or other vehicles from movement restrictions. However, the need for such signs is identified in Section 2A.06:

> Option:
>
> 13 State and local highway agencies may develop special word message signs in situations where roadway conditions make it necessary to provide road users with additional regulatory, warning, or guidance information, such as when road users need to be notified of special regulations or warned about a situation that might not be readily apparent. Unlike colors that have not been assigned or symbols that have not been approved for signs, new word message signs may be used without the need for experimentation.

State supplements to the MUTCD might provide bus-specific movement exemption signs not included in the national MUTCD.

A possible standard alternative to a DO NOT ENTER sign, depending on the design of the bus-only link, is the AUTHORIZED VEHICLES ONLY sign described in Section 2B.39(10).

Gates on roadways are described in Section 2B.68:

> Support:
>
> 02 A gate typically features a gate arm that is moved from a vertical to a horizontal position or is rotated in a horizontal plane from parallel to traffic to perpendicular to traffic. Traffic is obstructed and required to stop when the gate arm is placed in a horizontal position perpendicular to traffic. Another type of gate consists of a segment of fence (usually on rollers) that swings open and closed, or that is retracted to open and then extended to close.
>
> **Standard:**
>
> **05 Except as provided in Paragraph 6 [one-way roadway applications], gate arms, if used, shall be fully retroreflectorized on both sides, have vertical stripes alternately red and white at 16-inch intervals measured horizontally as shown in Figure 8C-1 [i.e., like railroad crossing gates].**

This section goes on to provide examples of some types of possible uses for gates, including enforcing a required stop (e.g., at a toll plaza) and periodically closing a roadway (e.g., reversible lanes, snow closures). Restricting access to authorized vehicles is not specifically listed as an application, but as it is not specifically prohibited, it can be applied on the basis of engineering study and judgment.

Discussion

Overview

Bus-only links provide direct bus access to streets or areas where it is undesirable or infeasible to provide automobile access. Typical applications are:

- Maintaining bus access through a neighborhood after a neighborhood traffic management program is implemented.
- Providing bus, bicycle, and pedestrian connections in areas planned to provide no vehicular connections between subdivisions.
- Providing direct bus access to a street where higher automobile traffic volumes are undesired.
- Providing direct bus turns onto a street at capacity-constrained intersections where it is infeasible to serve general traffic turns.
- Prioritizing 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.

Placement

An effective bus-only link should clearly communicate through signage, markings, and design that it is not intended for use by general traffic, so as to minimize inadvertent violations. Traffic calming design principles can be applied to the design of bus-only links—in particular, placing the entrance to a bus-only link at an intersection. When motorists have already committed to a roadway and discover in the middle of the block that it is closed to their direction of travel, they are much more likely to continue on, in violation of the signing (Ewing 1999). For links between neighborhoods, providing a driveway treatment at the link entrances can provide the impression that the link is a service roadway, rather than a public street. Red-colored pavement (an experimental treatment under consideration for inclusion in the MUTCD) can be considered for links that are continuations of public streets, to highlight the bus-only nature of the roadway.

Enforcement Options

Ideally, signage and pavement markings will be sufficient to effectively enforce bus-only links, as these are low-cost, low-maintenance items that do not impede buses or emergency vehicles. The experience of some jurisdictions, such as Ottawa, is that motorists in their jurisdictions generally respect the signage. The possible experience of a jurisdiction with traffic calming measures can also be relevant—for example, Berkeley, California found the violation rate for traffic diverters with emergency vehicle openings that only relied on signing for enforcement was 5–7% of the traffic formerly using the street (Smith and Appleyard 1980). Signage will not prevent all violations, but it may limit them to a level that stakeholders consider to be acceptable. Nevertheless, if a jurisdiction has no previous experience with signage-only violation rates for bus-only links or traffic calming devices, 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.

Law enforcement can be included to reinforce restrictions. Transit agencies could fund occasional police enforcement (or in some larger transit agencies, use their own police force), and consider it part of the operating cost for the route. Automated photo or video enforcement is another potential technique to controlling bus-only links, but most jurisdictions will require laws specifically authorizing automated enforcement.

Gate-type treatments can be effective at eliminating violations of the bus-only link, but have associated installation and maintenance costs and may be susceptible to vandalism (Smith and Appleyard 1980). If there is a mechanical or detection/communications problem with the gate, then bus traffic can be blocked until the gate is repaired. Parking lot–style gates and sliding gates are consistent with the MUTCD and are readily available on the market. Bollards are typically used outside the traveled way on roadways, so their application in a U.S. context would likely require an MUTCD experimentation request.

Trap-type treatments are not consistent with the MUTCD (i.e., would require an approved experimentation request) and would likely raise liability concerns in a U.S. context. Calgary retrofitted some of their pit traps with adjacent sliding gates, as trapped cars required assistance to be removed from the pit and the link was blocked in the meantime. Danish pit traps are designed with sloped entries that allow automobiles to back out of the trap on their own. 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). Although undercarriage preventers were included in some early traffic calming programs, they are not currently included in U.S. compilations of traffic calming best practice (e.g., Ewing 1999).

For bus-only links that rely on some sort of barrier (e.g., gates, traps), measures to prevent motorists from bypassing the barrier may need to be incorporated in the design. Bollards and trees have been frequently used in the international applications documented by this project.

Benefits

The potential benefit of bus-only links depends on the specific application. Links that provide transit connections where no other roadway connections exist can allow fixed-route and demand-responsive transit service to be provided to areas that would be inefficient to serve otherwise, due to the out-of-direction travel that would be required. Links that allow buses to make movements not permitted to general traffic save the extra travel time involved with making the movement indirectly. Links that are created as part of a neighborhood traffic management program can benefit transit through the reduction of traffic delays that were associated with the through traffic previously using a street and may also encourage mode shifts, if the change creates a travel time advantage for transit relative to a private vehicle.

Pedestrian and Bicycle Considerations

Bus-only links can incorporate provisions for pedestrian and bicycle passage, which can form part of a larger citywide pedestrian or bicycle network, or offer additional low-traffic opportunities for pedestrian and bicycle recreation within a neighborhood. At the same time, some neighborhoods may perceive new links as providing new access points to the neighborhood for criminals.

Stakeholders

Potential stakeholders for bus-only links vary depending on the application, but may include the following:

- The transit agency or agencies that would use the link.
- Local city or county engineering and planning staff, including staff with responsibility for pedestrian and bicycle planning.
- Emergency responders (e.g., fire, police, ambulance). All types of emergency responders will be interested in response time impacts. Law enforcement may be interested in enforcement needs and the potential impact on police activity (e.g., ability to surround a block to catch a suspect in hiding) (Smith and Appleyard 1980).
- School districts, when they provide school bus service.
- Neighborhood residents, when a new bus-only link is being created into or between neighborhoods.
- Local residents and businesses, if a through-traffic connection is being proposed to be removed as a part of the project.
- Bicycle advocacy groups, if a proposed link offers an opportunity to expand a community's bicycle network.
- Lawmakers, if laws need to be changed to permit bus-only links, establish fines for unauthorized use of bus-only links, or allow automated enforcement of bus-only links.

Recommendations

- Bus-only links can be considered when there is a need to provide transit service with the most-direct routing possible.
- The design of the link should clearly indicate to motorists that it is not for use by general traffic. Signage, 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.
- Bus-only links are preferably designed to accommodate pedestrians and bicycles, except when connecting to facilities where pedestrians and bicyclists are prohibited.

- Unless previous experience indicates a potential for violations, signing and marking could be adequate. However, enforcement could be integrated if the need arises.
- Parking-lot style gates are an option for restricting access to bus-only links to authorized vehicles, as are sliding gates. Planning and implementation should consider ongoing maintenance costs and the need to develop an operations plan for addressing situations when a gate will not open.
- Trap-type treatments, whether raised or lowered, are not recommended for U.S. applications, due to a lack of support for them in U.S. design standards.

SPECIAL BUS PHASE

Description

A special bus phase is a traffic signal phase included in the traffic signal cycle to serve bus movements that cannot be served concurrently with other traffic. The typical application allows a bus turning movement from a non-standard location, such as making a left turn from a right-side bus lane, making a right turn from a left-side bus lane, or making turns into and out of a median bus lane. Figure E-6 illustrates the operation of a left turn from a right-side bus lane.

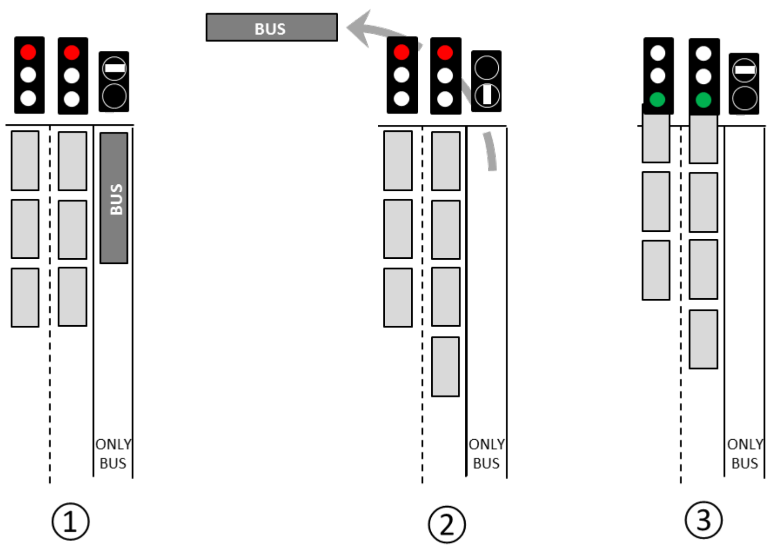


Figure E-6. Example of Special Bus Phase Operation

Other types of transit preferential treatments also integrate bus phases into the signal cycle—for example, queue jumps, queue bypasses, pre-signals, and certain types of bus-only links. The difference is these phases are designed to give buses an advantage over other traffic, even though the basic bus movement could have been accommodated without the preferential treatment. A *special bus phase,* as defined here, serves bus movements that cannot be accommodated with the normal rules of the road.

Figure E-7 shows two former implementations of special bus phases allowing bus turning movements from the opposite side of the street. As discussed in the Implementations subsection next, neither of these special bus phases is used any more, for reasons unrelated to how they operated.

(a) Eugene, Oregon (b) Richmond, B.C., Canada

Figure E-7. Examples of Special Bus Phase Implementations

Implementations

San Francisco

A special bus phase allowed buses to make right turns onto Howard Street from a left-side bus lane on First Street. Both streets are one-way. The left-side bus lane was implemented to allow buses to avoid delays caused by right-turning traffic at intersections along First Street and to provide a bus stop on the same side of the street as the former Transbay Terminal. The special bus phase allowed buses to continue on their route without having to weave across three lanes of backed-up traffic, and allowed the turn to be made without interference with pedestrian crossing movements. The combination of the three-block bus lane and the special bus phase saved buses an average of 1.5 minutes (38%) during the weekday afternoon peak period, compared to the previous mixed-traffic operation. In addition, travel time reliability improved, with the standard deviation of travel times through this section being reduced from 103 seconds to 44 seconds (Mirabdal and Thesen 2002). After the closure of the Transbay Terminal in preparation for the construction of a new Transbay Transit Center, the bus line was re-routed and the special bus phase is no longer in use.

Eugene, Oregon

The initial segment of the EmX bus rapid transit line (BRT) includes a bi-directional bus lane along the left side of a one-way westbound street, East 11th Street. The route turned at Mill Street, which required westbound buses to make a right turn from the left lane, and a special bus phase was used to facilitate that turn (see Figure E-7a). Later, the bus route was realigned so that westbound buses stayed on East 11th Street when approaching the downtown Eugene Station transfer center, both to reduce the number of turns on the westbound route and to prepare for a future BRT extension west of downtown Eugene, and the special bus phase was no longer needed. The westbound bus signal now operates in a queue jump mode, allowing westbound buses to depart ahead of parallel traffic so the buses can merge across the street into a new right-side bus lane that begins one block to the west.

Richmond, B.C., Canada

The Airport Station transit center was located in the southeast quadrant of the intersection of Russ Baker Way and Miller Road and served as one terminus of the bus line to Vancouver International Airport. When exiting the transit center, buses bound for the airport had to make a left turn onto Miller Road from bus lanes located on the right side of Russ Baker Way (see Figure E-7b), while northbound BRT buses bound for downtown Vancouver had to merge into the adjacent general traffic lanes. A special bus phase was used to facilitate both bus movements. After the Canada Line rail extension opened to the airport, the transit center was closed and the special bus phase is no longer in use.

Existing Implementation Guidance

AASHTO Transit Guide

AASHTO (2014) identifies 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 5.5.5.2); a pre-signal is identified as a potential alternative. AASHTO also identifies the need for a special bus phase when a high volume of buses make right turns from a median bus lane (Section 5.6.2.2); a queue jump at an upstream intersection or an exit lane from the median bus lane that allows buses to merge into the general traffic lanes are also presented as options when a low volume of buses needs to turn right.

MUTCD

The MUTCD allows the use of light rail transit (LRT) signals (e.g., vertical and horizontal bar signals) to control bus movements, as discussed in Section 4D.27:

> Option:
>
> 18 If engineering judgment indicates that light rail transit signal indications would reduce road user confusion that might otherwise occur if standard traffic signal indications were used to control these movements, light rail transit signal indications complying with Section 8C.11 and as illustrated in Figure 8C-3 may be used for preemption or priority control of the following exclusive movements at signalized intersections:
>
> A. Public transit buses in “queue jumper” lanes, and
>
> B. Bus rapid transit in semi-exclusive or mixed-use alignments.

Discussion

Overview

Special bus phases are a potential option when bus turning movements need to be made from unconventional locations. Designs must account for conditions where other traffic needs to be warned about the unconventional movement (e.g., BUS SIGNAL signage, a special sign depicting the bus maneuver, dotted pavement markings). 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.

From an operations perspective, the time required to serve the special bus phase will take green time away from the other movements at the intersection, traffic analyses must determine whether the intersection has sufficient capacity to accommodate the extra phase. In addition, traffic laws may need to be changed to allow buses to make signal-controlled left turns from a lane to the right of other traffic, or right turns from a lane to the left of other traffic.

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 while at the same time as 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 is to start the median bus lane's bus phase before parallel traffic receives a green signal at an upstream intersection, thus giving buses a gap in traffic that allows them to weave out of the busway and into the correct general traffic lane for their turn at the downstream intersection. Another alternative is to provide a mid-block "slip ramp" exit from the median bus lane that allows buses to merge into general traffic.

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 allows 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.

Stakeholders

Potential stakeholders for special bus phases include the following:

- The transit agency or agencies that will use the special bus phase.
- Traffic signal and traffic operations engineers from the appropriate roadway jurisdiction.
- Lawmakers, if laws need to be changed to permit transit signals or allow for buses to make left (right) turns from lanes to the right (left) of through general traffic lanes.
- Law enforcement, particularly if this will be the first application of special bus phases in an area.

Recommendations

- Because of the unconventional turning movements involved with special bus phases, first investigate whether another more-conventional treatment (e.g., bus-only turn lane, pre-signal, queue jump) would meet the need.
- Check whether local or state traffic laws permit buses to make the desired unconventional turning movement.
- Check bus turning paths and the need to relocate stop bars when applying this treatment.
- Determine how the extra time required for the special bus phase would affect intersection operations.
- Special bus phases are needed to serve bus turning movements from a median bus lane. Depending on conflicting vehicular, bicycle, and pedestrian traffic, they may also be needed to serve bus turning movements into a median bus lane.
- Special bus phases may be considered for non-standard turning movements from right- or left-side bus lanes when it is desirable to provide a near-side bus stop at an intersection where a bus route turns, or when the standard turning movement operates over capacity and it is desired to give buses a path around traffic queues.
- When a mix of through and turning bus traffic will use a special bus phase, consider the need for and ability to provide separate through and turning bus lanes, to minimize through bus delays and minimize the amount of time required to serve the special bus phase.

TRAFFIC SIGNAL SHADOWING

Description

Shadowing is a technique where a bus at an unsignalized intersection triggers a call for a phase at a nearby signalized intersection. When that phase is served, a gap in traffic is created that allows the bus to complete its turn. Figure E-8 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 Step 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) and a call is placed for the left-turn phase at the downstream intersection, even though no vehicles are waiting to make the left turn.

In Step 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 Step 3, the gap has reached the unsignalized intersection and the bus can make its turn.

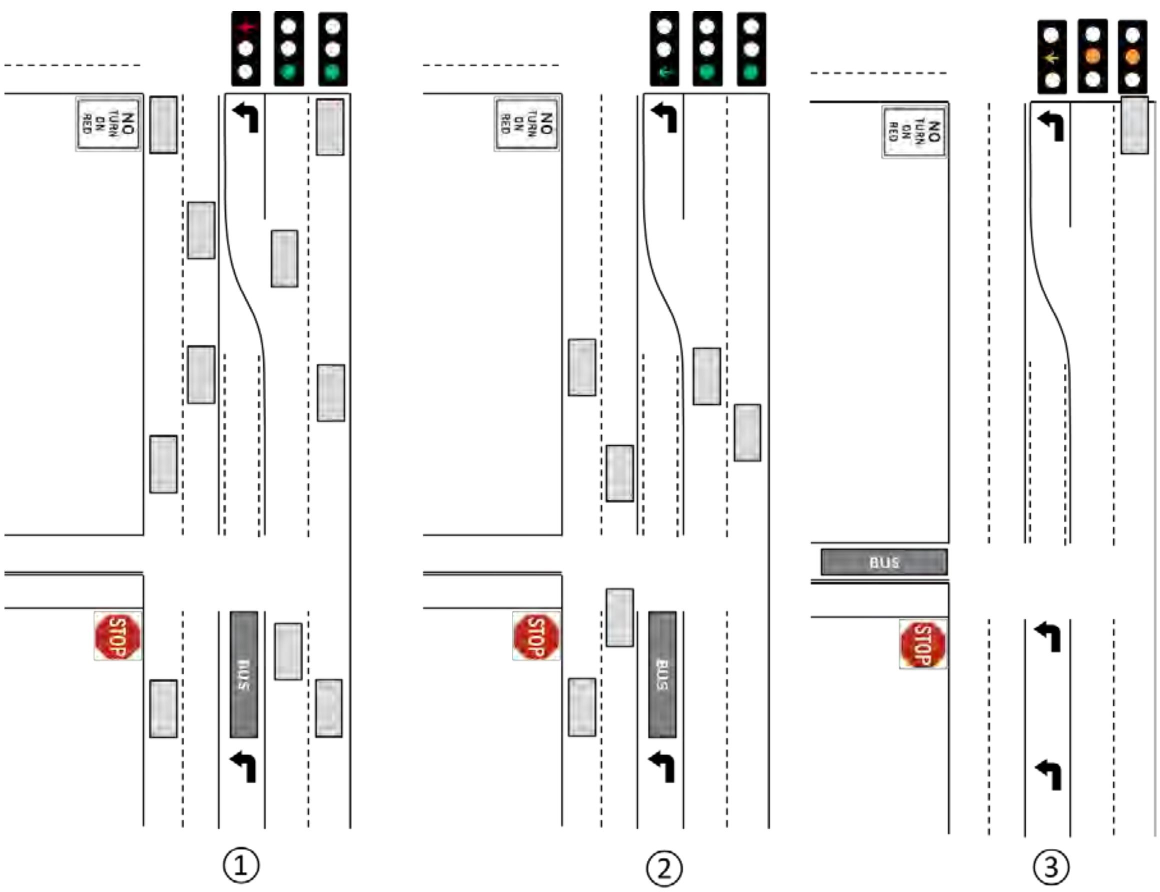


Figure E-8. Example of Traffic Signal Shadowing

Implementations

Portland, Oregon

TriMet uses traffic signal shadowing at the Barbur Transit Center. 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 one-way into the transit center from the traffic signal.

Calgary and Edmonton, Canada

Calgary and Edmonton 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.

Existing Implementation Guidance

AASHTO Transit Guide

Traffic signal shadowing is not mentioned in AASHTO's transit guide (2014).

Canada

The Transportation Association of Canada guidelines (Corby et al. 2013) suggest using a "traffic signal required by transit" (i.e., a traffic signal installed solely to serve transit needs that might not be justified by general traffic needs) in situations where traffic signal shadowing might be used. 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.

MUTCD

Traffic signal shadowing is not mentioned in the MUTCD. The MUTCD does not permit half-signals (Section 4C.05.06) or pedestrian hybrid beacons (e.g., HAWK signals, Section 4F) at intersections. Shadowing in conjunction with a downstream pedestrian hybrid beacons (e.g., HAWK signals) at an intersection would require an experimentation request to FHWA. The MUTCD does not provide a warrant for installing a traffic signal solely on the basis of transit needs; therefore, a counterpart to the Canadian "traffic signal required by transit" would require an experimentation request to FHWA. The MUTCD allows traffic signal control for highway–LRT grade crossings in certain circumstances (Section 8C.03.05), but no provision is made for BRT or other bus transit operations (the use of LRT signals for bus operations, as discussed in Sections 4D.27.18 and 8C.11.03, are predicated on the intersection already being signalized for reasons other than transit needs).

Discussion

Overview

Traffic signal shadowing is typically contemplated as a potential transit preferential treatment only because the MUTCD does not provide a means for installing traffic signals solely on the basis of bus transit needs. 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 across busy streets that have a long distance between traffic signals.

Stakeholders

Potential stakeholders for a traffic signal shadowing treatment include the following:

- The transit agency or agencies that will use the special bus phase.
- Traffic signal and traffic operations engineers from the appropriate roadway jurisdiction.

Recommendations

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 coordinated signal system, crash experience, or roadway network 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, or 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 these road users in most cases do not prevent buses from using the gap that is created.
- 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 turn in two stages.

Further research should investigate (1) the potential need for a bus transit–specific signal warrant and (2) the potential to implement a transit hybrid beacon, similar to the emergency vehicle and pedestrian hybrid beacons already provided in the MUTCD.

BUS BOARDING ISLANDS

Description

Boarding islands are bus stops on raised concrete islands within the roadway. They can be a part of a larger traffic channelizing island used for other purposes, such as those used to separate right-turning traffic from the rest of the intersection, or they can be purpose-built to serve transit boardings and alightings. Figure E-9 illustrates three possible boarding island configurations. For simplicity of presentation, bicycle facilities are not shown, but can be included as part of the design, as described later in this section.

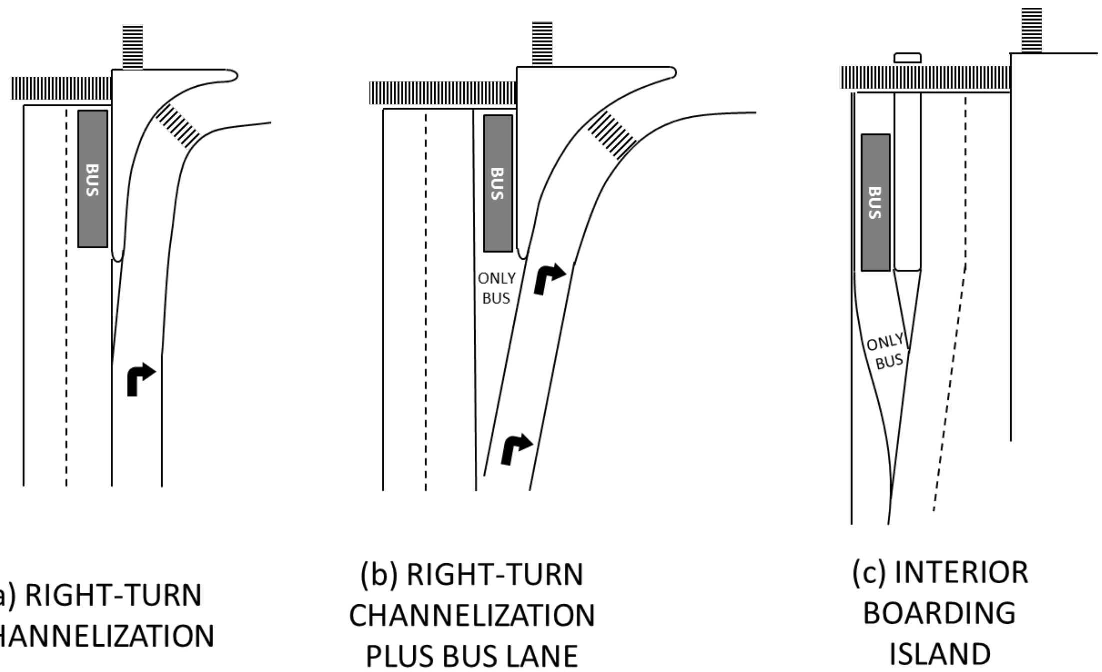


Figure E-9. Illustrative Boarding Island Configurations

Figure E-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-foot by 5-foot 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 desired areas.

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

Figure E-9(c) shows a boarding island in the interior of the roadway, served by a short bus lane. The configuration shown in the illustration could support buses transitioning into a median bus lane 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. 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 special bus phase would be required for buses departing the stop. The bus stop itself would be configured similar to median bus stops on bus rapid transit lines, with a ramp connecting the platform to the crosswalk. As with the other boarding island configurations, the island would need to be at least 8 feet wide to provide the minimum required ADA clear area and pedestrian fencing or other similar barriers may need to be considered.

Implementations

San Francisco

An ADA-compliant boarding island serves a left-side bus lane on Bush Street just before its intersection with Battery and Market Streets. A similar boarding island was constructed to serve a left-side bus lane stop at the Transbay Terminal (Mirabdal and Thesen 2002). The latter island no longer exists, due to the relocation of the Transbay Terminal while its replacement is being constructed. 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).

Copenhagen, Denmark

Two interior bus islands serve northbound buses along Øster Farimagsgade in central Copenhagen. The street's intersection with Sølvgade is complicated, as Sølvgade splits into a pair of one-way streets and significant right-turning and bicycle traffic exists along the right side of Øster Farimagsgade, which creates challenges in developing a bus stop location. Therefore, a short bus lane has been developed on the left side of the northbound lanes, serving a near-side bus stop on a boarding island. At the street's northern end at Dag Hammarskjölds Allé, a similar arrangement is used to create a near-side bus stop prior to the bus route turning left.

Existing Implementation Guidance

AASHTO

AASHTO's transit guide (2014) 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).

MUTCD

The MUTCD provides object markers as an option for marking the end of median islands (Section 2C.64).

> Option:
> 02 To provide additional emphasis, a Type 1 or Type 3 object marker may be installed at or near the approach end of a median island.

Chapter 3I provides guidance and requirements for pavement markings and delineation for islands. Section 3I.06 specifically discusses the use of pedestrian islands and medians. As always, state and local roadway design manuals should be consulted to determine how the MUTCD's standards and guidance are translated into specific local design requirements.

Discussion

Overview

Right-turn channelizing islands can provide a location for a bus stop in situations where it would be desirable to provide a near-side bus stop, but the channelizing island prevents locating the bus stop in the right-turn lane itself (or would require placing the stop farther away from the intersection than desired). Channelized right turns are more likely to be found at suburban intersections, due to the greater right-of-way availability in those locations and the higher traffic speeds.

As discussed in Appendix D, far-side stops generally result in lower bus delays and thus shorter travel times, but there are instances when a near-side stop may be preferred. These instances include locations where a major passenger generator is located on the near-side of an intersection, locations where a short transfer connection between transit lines or modes is desired, and locations where it is possible to employ other near-side transit preferential treatments, such as queue jumps and special bus phases.

A bus stop could also potentially 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 buses can stop out of the traffic lanes, without other vehicles stopping behind them and potentially blocking the intersection. Design considerations include: managing the area where cross-street right-turning traffic enters the main street, managing conflicts with buses exiting the bus stop, and addressing the potential for bus shelters and stopped buses to block the view of right-turning traffic entering the street.

Interior boarding islands can provide a location for bus stops along left-side and median bus lanes (eliminating the need for buses with doors on both sides), along interior bus lanes, and at intersections where a bus route turns left, but a near-side stop is desired.

Transit Considerations

The transit agency will need to consider how many buses are likely to simultaneously use a bus stop on a boarding island, as an island may have sufficient area to serve one bus, but not two. The lengths of the buses that will use the stop and the locations of their doors will also need to be considered, when evaluating whether sufficient island width exists to safely serve passengers exiting from all doors. As with other types of far-side stops, the potential for buses to block the intersection while waiting to access the stop is also a consideration.

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 or raised bicycle lane through the island for bicyclists that separates the bus stop platform area from the remainder of the island. To minimize bicycle–pedestrian conflicts, the parallel crosswalk would need to be set back from the intersection so that it is located 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 buses can cross into the bicycle lane to serve the stop.
- If no bicycle facility exists, use shared lane markings (“sharrows”) to guide bicyclists through the bus stop area.

See the “Managing Bus and Bicycle Interactions” section for more details about each of these treatments.

Left-side bus lanes—similar to left-side bicycle lanes, discussed in the “Managing Bus and Bicycle Interactions” section—can separate bus and bicycle traffic by providing facilities for the two modes on opposite sides of the street (or direction of travel on the street). In this situation, interior boarding islands are a supporting measure for the left-side bus lanes, allowing bus stops to be placed as needed along the left-side bus lanes.

Stakeholders

Potential stakeholders for bus boarding islands vary depending on the application, but may include the following:

- The transit agency or agencies that would use the boarding island.
- Local city or county engineering and planning staff, including staff with responsibility for pedestrian and bicycle planning.
- Bicycle advocacy groups.

- Organizations representing vision-impaired pedestrians.

Recommendations

The following characteristics make a site a potential candidate for a boarding island on a right-turn channelizing island:

- Suburban locations 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, special bus phase, or other near-side transit preferential treatment.
- Ability to accommodate bicycle facilities that may be present on the street.
- For a far-side channelizing island, space to provide a short bus lane and the ability to manage potential merging conflicts and sight distance issues for right-turning traffic entering the street.

Interior boarding islands are necessary supporting infrastructure when bus stops are desired to be provided along interior, left-side, and 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.