Title
Transit Signal Priority Research Tools

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Publication Date
2008-05-01

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2008	12/24/2004 – 3/31/2007

4. TITLE AND SUBTITLE

Transit Signal Priority Research Tools

5. FUNDING NUMBERS

CA-26-7049-00

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

UCB-ITS-PRR-2008-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, D.C. 20590

10. SPONSORING/ MONITORING AGENCY REPORT NUMBER

FTA-CA-26-7049-2008.1

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Available From: National Technical Information Service/NTIS, 5285 Port Royal Road, Springfield, Virginia 22161. Phone 703.605.6000, Fax 703.605.6900, Email [orders@ntis.d.gov]

12b. DISTRIBUTION CODE

FTA/TRI-11

13. ABSTRACT (Maximum 200 words)

This report presents the results of a research project that addresses Transit Signal Priority (TSP) deployment issues. The report reviews National Transportation Communications for ITS Protocol (NTCIP) 1211 Signal Control and Prioritization (SCP) standards, defines five SCP scenarios, and describes how the SCP scenarios can be applied differently based on TSP priority and operating policies. The report provides an overview of a number of TSP systems, including centralized TSP, two discrete TSP systems based on loop detection and Global Positioning System (GPS) technologies, and an Adaptive Transit Signal Priority (ATSP) system. A comparison of the different TSP deployments, and guidance on the necessary infrastructure required to implement these TSP systems, are provided. The report also discusses TSP evaluation methodologies, including recommended measures of effectiveness (MOE's) and data required for performing a quantitative assessment. Evaluations of a number of TSP deployment sites are documented to demonstrate how the benefits of TSP to transit and the impacts of TSP to traffic operations are assessed using the recommended approaches. Finally, the report provides guidance on TSP planning and analysis methods, such as simulation and regional modeling tools.

14. SUBJECT TERMS

Transit Signal Priority, Priority Request Generator, Priority Request Server, Signal Control and Prioritization, Traffic Response Field Master, Traffic Management Center, Transit Management Center, National Transportation Communications for ITS Protocol, Transit Communications Interface Profiles, Centralized TSP Architecture, Distributed TSP Architecture, Evaluation, Measures of Effectiveness, Benefits, Costs, Modeling and Simulation Tools

15. NUMBER OF PAGES

126

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

U.S. Department
of Transportation
**Federal Transit
Administration**

Transit Signal Priority Research Tools

May 2008

DISCLAIMER NOTICE

Transit Signal Priority Research Tools

Final Report

May 2008

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Report No. FTA-CA-26-7049-2008.1

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List of Acronyms

AP	Access Point
APC	Automatic Passenger Counter
API	Application Programming Interface
ATC	Advanced Transportation Controller
ATCS	Adaptive Traffic Control System or Automated Traffic Control System
ATP	Arrival Time Predictor
ATSAC	Automated Traffic Surveillance And Control
ATSP	Adaptive Transit Signal Priority
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
BRT	Bus Rapid Transit
CAD	Computer-Aided Dispatch
DSRC	Dedicated Short Range Communications
ETA	Estimated Arrival Time
FIFO	First In, First Out
GPRS	General Packet Radio Service
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITS	Intelligent Transportation Systems
LACMTA	Los Angeles County Metropolitan Transportation Authority
LADOT	Los Angeles Department of Transportation
NEMA	National Electronics Manufacturers Association
NTCIP	National Transportation Communications for ITS Protocol
PID	Parameter Identification
PRG	Priority Request Generator
PRS	Priority Request Server
RFID	Radio Frequency Identification
SAE	Society of Automotive Engineers
SBC	Southwestern Bell Corporation
SCP	Signal Control and Prioritization
SMTP	Simple Mail Transfer Protocol
TMC	Traffic Management Center
TPM	Transit Priority Manager
TPS	Transit Priority System
TRFM	Traffic Response Field Master
TSCP	Traffic Signal Control Program
TSP	Transit Signal Priority
TTA	Time To Arrival
UDP	User Diagram Protocol
UTC	Coordinated Universal Time
VTA	Santa Clara Valley Transit Authority
WLAN	Wireless Local Area Network

Acknowledgements

This report presents the results of a research effort undertaken by the California Partners for Advanced Transit and Highways (PATH) Program of the University of California at Berkeley; Kittelson & Associates, Inc.; and the Center for Urban Transportation Research (CUTR) of the University of South Florida, with sponsorship and funding from the United States Department of Transportation (USDOT) Federal Transit Administration (FTA) and Research and Innovative Technology Administration (RITA) ITS Joint Program Office.

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Kittelson & Associates, Inc.: Scott Beaird and Peter Koonce

CUTR: Larry Hegen

Project management and ccontractual assistance was provided by Z. Sonja Sun of the California Department of Transportation (Caltrans). USDOT project management and direction was provided by Sébastien Renaud, Steven Mortensen, and Michael Baltes of the FTA, and Brian Cronin (formerly of the FTA) and Yehuda Gross of the RITA ITS Joint Program Office. Technical assistance and support was provided by Matthew Hardy of Noblis.

1 Overview

This report documents the results of a study that addresses Transit Signal Priority (TSP) implementation issues from the following perspectives:

1) The emerging standard for TSP implementation
2) Distinguished TSP implementation, supported by deployment examples
3) Measures of effectiveness (MOE) and objective evaluation methods

The report compliments earlier efforts funded by the United States Department of Transportation (USDOT) entitled *Overview of Transit Signal Priority* and the *Transit Signal Priority Handbook*

The report first reviews five scenarios defined in the National Transportation Communications for ITS Protocol (NTCIP) 1211 Signal Control and Prioritization (SCP) and Transit Communications Interface Profiles (TCIP) standards and assesses the applicability to TSP systems. Based on the assessment, the project provides guidance on the infrastructure required for each SCP scenario in order to support the implementation of various types of TSP in different transit operating environments and policies. The establishment of standards is an important step in the application of TSP, which permits a variety of users (e.g., transportation management centers, transit management centers, transit fleet vehicles, traffic signal controllers) to communicate with each other using equipment from different manufacturers. The reports points out that although historically many TSP implementations have been limited by existing systems, technologies have advanced such that opportunities exist for a full implementation of the NTCIP 1211 standard. The implementation of these standards will enable an advanced, conditional TSP system that meets the functional requirements.

The report also addresses several TSP technology and implementation issues. It assessed the key components of various TSP systems for implementation, including transit vehicle detection, traffic signal control hardware and software, bus automatic vehicle location (AVL) systems, communications technologies, and traffic and transit management centers. It assesses in detail the working principles of these components and their functions in each type of TSP system, and provides performance and cost data wherever information was available.

The report then reviews and discusses in detail a number of TSP deployment examples, including centralized TSP deployed by the Los Angeles Department of Transportation (LADOT), two discrete TSP systems based on loop detection and Global Positioning System (GPS) technologies separately deployed by the Los Angeles County Metropolitan Transportation Authority (LACMTA) and Santa Clara Valley Transit Authority (VTA), and an Adaptive Transit Signal Priority (ATSP) system implemented at SamTrans. Based on the evaluation and comparison of different TSP deployments, the project provided guidance on the necessary infrastructure required to implement these TSP systems. The centralized TSP is built upon the centralized traffic control system and the TSP decisions are made by the central traffic control system, whereas in the decentralized case, TSP decisions are made locally at the intersections. The two decentralized TSP systems differ greatly in terms of transit vehicle detection, vehicle to intersection communications, and signal controller and system software. Also reviewed was an ATSP system, which provides priority, if warranted, to transit vehicles while trying to balance the tradeoff between bus delay savings and the impacts on the rest of the traffic. This system utilizes a GPS/AVL system instrumented on buses to continuously monitor bus locations, predict bus arrival times to intersections, and make real time decisions adaptive to the movements of transit vehicles, traffic conditions, and signal status. The report evaluates the hardware, software, and system capabilities of various systems, compares costs, and discusses the implementation opportunities of each type of TSP system.

The report discusses TSP evaluation approaches, including a set of MOEs and a comprehensive evaluation method developed for quantitatively evaluating the performance of a TSP system in order to achieve comparable evaluation results among different TSP implementations. The MOEs address reliability, travel speed/time, operating costs, pollutant emissions, ridership, safety, and TSP performance for transit and arterial components. The report reviews a number of evaluation tests conducted at the TSP deployment sites using the recommended MOEs and the evaluation approaches. The results of these evaluation tests provide quantitative evaluation data on the benefits of TSP to transit and the impacts of TSP to traffic operations. Through these case studies, the report presents how MOEs and evaluation methods can be implemented.

Finally, the report provides guidance on TSP planning and analysis methods, such as simulation and regional modeling tools that can be used for planning TSP deployments. Macroscopic ridership models are used to predict ridership changes with a TSP project, while macroscopic and microscopic traffic models estimate how traffic and transit operational conditions would change in response to TSP implementations.

2 Introduction

2.1 Project Background

TSP is an operational strategy that facilitates the movement of in-service transit vehicles, either buses, streetcars or light rail vehicles through signalized intersections. TSP offers a cost effective approach to pursuing a number of valuable objectives including: reduced transit travel times, improved schedule adherence, improved transit efficiency, and increased road network efficiency as measured by person mobility.

New advances in Global Positioning Systems, detection and communication, and control strategies have overcome many problems with early systems and increased interest in implementing TSP for Bus Rapid Transit (BRT) and other transit operations. The increased capabilities of these advanced systems have led to a dramatic increase in operational and planned TSP deployments across the U.S. TSP has come to be considered a key component of the Federal Transit Administration's BRT initiative to use ITS and other innovations (e.g. vehicle design, right of way improvements) to attain the features of rail rapid transit systems (e.g. minimum delay, reliability, identity) while keeping the advantages of bus transit (e.g. flexibility, cost, access/egress).

However, issues and hurdles still remain regarding the planning, design, implementation, and operation of TSP systems throughout the Nation. Consequently, the FTA has sponsored a number of activities to help identify and address these issues and hurdles. These include:

- Development and Publication of "An Overview of Transit Signal Priority" (ITSA/APTA) in 2002, and release of a revised and updated version in 2004
- A Research Needs Assessment Workshop (02/03)
- Three 2003 Regional Transit/Traffic Agency TSP Workshops
- Development of the "Planning & Implementing TSP: A Guide to Best Practice" (Initiated 03/04)
- TSP and Traffic/Transit Operations Support (Initiated 03/04)
- TSP Deployment Workshops

This project builds upon these activities and provides support to address a number of specific issues concerning the identification of appropriate TSP strategies in specific situations, the incorporation of TSP into various transit systems, the identification and use of appropriate standards, and implementation and operation of TSP in general.

2.2 Project Purpose

The purpose of this project is to help transit agencies improve travel times and reliability of transit trips through Transit Signal Priority. While TSP has been successfully implemented across the nation there are a number of issues that transit agencies face when designing and implementing TSP.

The objectives of this report include the following:

- Provide examples of different TSP implementations in the U.S.
- Provide guidance on the infrastructure required to implement SCP scenarios as defined by NTCIP 1211.
- Provide guidance on the transferability of the LA DOT TSP software.
- Provide guidance on TSP planning and analysis methods such as simulation and regional modeling tools.
- Provide guidance on the selection of MOE's to assess the impacts of TSP on transit and traffic operations.

2.3 Report Organization

The report has been organized as follows:

Chapter 1: Overview

Chapter 2: Introduction

Chapter 3: TSP Implementation Scenarios

- Define NTCIP 1211 SCP standards and the five SCP scenarios
- Describe how the SCP scenarios can be applied differently based on TSP priority and operating policy

Chapter 4: TSP Technology and Implementation

- Provide an overview of the different TSP technologies including vehicle detection, hardware and software, and automatic vehicle location (AVL) systems
- Define the technologies necessary to implement NTCIP 1211 standards

Chapter 5: Evaluation of TSP Performance

- Define Measures of Effectiveness for evaluating TSP performance
- Define modeling and simulation tools that can be used to assess TSP
- Evaluate and document the benefits of TSP to transit and the impacts of TSP to traffic operations.

3 TSP Implementation Scenarios – Centralized and Distributed Architecture

3.1 Introduction

This chapter describes the standards related to the assessment and implementation of different SCP scenarios. It identifies desired points of interaction and input with designated stakeholders related to TSP for Bus Rapid Transit (BRT). The establishment of standards is an important step in the application of TSP. Standards permit a variety of users (e.g., transportation management centers, transit management centers, transit fleet vehicles, traffic signal controllers, etc.) to communicate with each other using equipment from different manufacturers.

3.1.1 The NTCIP 1211 Standard

The National Transportation Communications for ITS Protocol (NTCIP) effort is a joint undertaking of the National Electronics Manufacturers Association (NEMA), the American Association of State Highway and Transportation Officials (AASHTO), and the Institute of Transportation Engineers (ITE) to develop standards to be applied to traffic control systems. The NTCIP 1211 standard, *Object Definitions for Signal Control and Prioritization (SCP)*, was developed to establish standards for use in implementing TSP applications within traffic signal systems.

The NTCIP 1211 SCP Concept of Operations is comprised of two primary elements, the Priority Request Generator (PRG) and a Priority Request Server (PRS). A transit vehicle, which could be a light rail train, bus, or other transit vehicle, through its agent, the PRG, submits a request for priority to the PRS. These two elements can be thought of as a logical process that could be physically implemented in more than one way, as discussed further in the document. The standardization occurs at the interface of these processes and represents the objects developed by NTCIP 1211. The two primary interfaces are (1) between PRG and PRS and (2) between PRS and the traffic signal controller coordinator, which implements special coordination operation.

Another element of the NTCIP SCP Concept of Operations, which directly relates to the traffic signal software, is the concept of granting priority while maintaining coordination with adjacent intersections. The functionality identified is intended to work in conjunction with the signal coordination object definitions and functions as defined in NTCIP 1202 – Object Definitions for Actuated Signal Controllers, also developed by the NTCIP Joint Committee. NTCIP 1211 includes a number of signal timing parameters that modify normal coordination parameters to allow implementation of a priority strategy. The strategies and timing parameters are under the control of the traffic signal system operator.

NTCIP 1211 also defines a Management Information Base (MIB) or data dictionary of parameter controls and status information for SCP related to:

1. Generating and monitoring the status of a request for priority from a source to a logical entity referred to as the Priority Request Server

2. Passing a prioritized list of priority requests to a controller and monitoring the status of the controller responses
3. A set of configuration parameters to manage the process of receiving and responding to priority requests

The MIB was created in April 2004 by the NTCIP 1211 Signal Priority Working Group. This information is documented in the NTCIP 1211 report Objects Definitions for Signal Control and Prioritization.

The NTCIP 1211 standard addresses the four likely signal control priority scenarios and use cases that can be used to provide a logical architecture for implementation of TSP. They include the following:

- Scenario 1 – Fleet Vehicle Priority Request Through Fleet and Traffic Management Centers
- Scenario 2 – Fleet Management Priority Request Through Traffic Management Centers
- Scenario 3 – Traffic Management Priority Request
- Scenario 4 – Fleet Vehicle Priority Request

3.1.2 The TCIP Standard

The Transit Communications Interface Profiles (TCIP) Standard Working Group (WG) comprises the nation's foremost authorities related to Transit Standards. The TCIP WG 10 has addressed the transit portions of the NTCIP as it relates to transit signal priority. The Working Group developed an interface standard as part of the TCIP that defines standardized mechanisms for the exchange of information in the form of data among transit business systems, subsystems, components, and devices.

The intent of this development process is to provide transit industry standards as a component of the US Intelligent Transportation Systems (ITS) program. The latest version of the standard, as described in the TCIP 3.0 Draft Standard for Transit Communications Interface Profiles report (dated 11/24/04), addresses the four signal control priority scenarios to be further assessed in this FTA research, and a fifth scenario that accommodates implementations where the transit vehicle communicates directly to the roadside, but does not generate priority requests onboard.

The five SCP scenarios provide a logical architecture for implementation of TSP in different transit and traffic operating environments. The purpose of the SCP scenarios is to show where logical decisions can be made and where standard NTCIP messages can be produced and transmitted. As mentioned at the beginning of this document, the two primary elements in any TSP system are the PRG and the PRS. The defining characteristics of each of the five scenarios are where the PRG and PRS are located and what inputs are being transmitted and received.

At a broader level, these scenarios can be categorized according to whether they are implementing TSP in a Centralized or Distributed Architecture. These architectures are based upon the traffic signal system, on-board vehicle equipment, and communication infrastructure. In the context of these system configurations, this report then details five possible scenarios: three central system alternatives and two distributed system alternatives. It describes the functional requirements of the five scenarios as well as some challenges to implementation and example applications.

3.2 Signal Control and Prioritization Scenarios for TSP

3.2.1 Centralized TSP Architecture

A centralized priority system involves the Transit Management Center and/or the Traffic Management Center (TMC) in the decision making process. Under a centralized priority system, the Priority Request Generator, the Priority Request Server, or both are located in one of the management centers. This system is advantageous in situations where the local jurisdictions have their signal controllers connected to a centralized system and managed by a Traffic Management Center with second-by-second communication. This section describes the three NTCIP SCP scenarios that have been developed for implementing a centralized priority system and the hardware and communication requirements necessary.

3.2.1.1 Scenario 1

The first centralized priority system alternative, Scenario 1, is represented in Figure 3-1. Under Scenario 1, the Priority Request Generator is located on the transit vehicle and there is no direct communication connection between the vehicle and the traffic signal controller. The transit vehicle transmits a priority request to the Transit Management Center, which then forwards the request to the Priority Request Server. The Priority Request Server may exist as a physical device either at the Traffic Management Center or in the traffic signal controller.

Requirements of Scenario 1

Implementation of this scenario requires the transit vehicle to be capable of generating and transmitting a NTCIP 1211 compliant request for priority. Therefore, the transit vehicle must be capable of determining its location and, if conditional priority is being used, generating a request based on specific operating characteristics (e.g. schedule adherence, ridership). Furthermore, the transit vehicle must have the proper communication equipment in order to transmit a NTCIP 1211 message. Some communication devices, such as current generation optical devices, do not have the ability to transmit a NTCIP 1211 standard message.

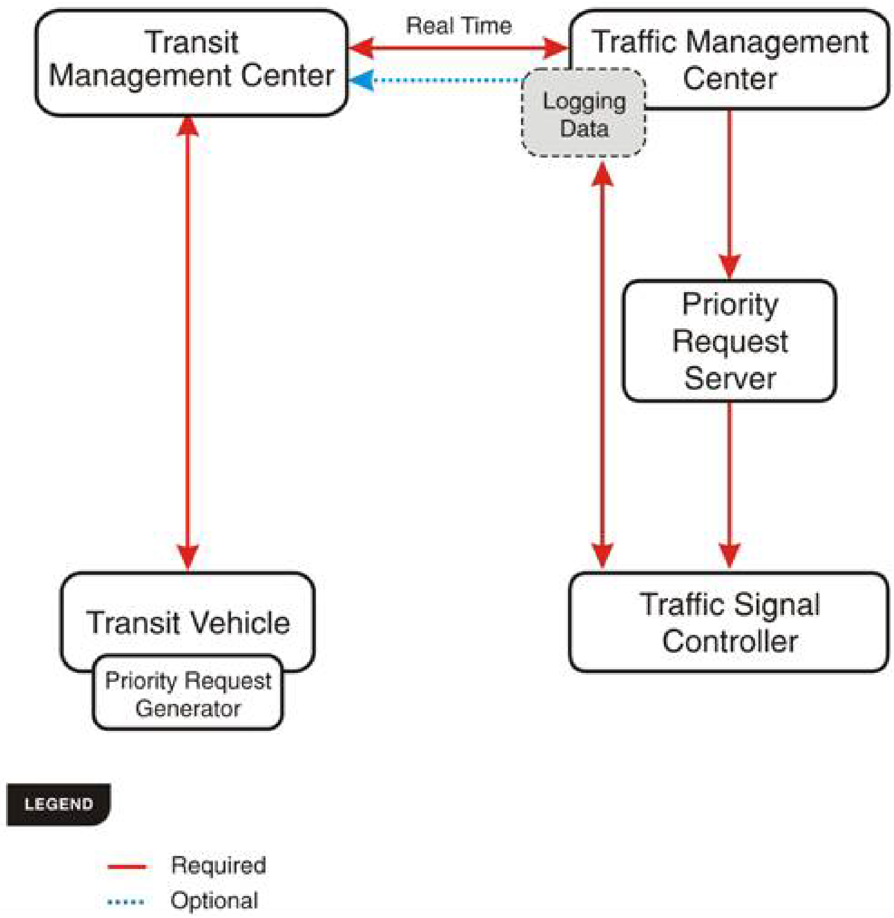


Figure 3-1: Scenario 1 (Centralized)

In order to be effective, this alternative requires second-by-second communication between the transit vehicle and the Transit Management Center, between the Transit Management Center and the Traffic Management Center, and between the Traffic Management Center and the local signal controllers. The effectiveness and efficiency of a TSP implementation quickly degrades as the communication latency increases. The polling rates used by many transit agencies to receive messages and data from their transit vehicles may preclude a Scenario 1 implementation.

3.2.1.2 Scenario 2

Scenario 2, shown in Figure 3-2 , differs from Scenario 1 in that the Priority Request Generator is located in the Transit Management Center rather than on the transit vehicle. In this case, the Transit Management Center makes a decision to request priority, which is then forwarded to the Priority Request Server through the Traffic Management Center. As in Scenario 1, the Priority Request Server may be located in the Traffic Management Center or in the traffic signal controller cabinet.

Requirements of Scenario 2

To be most effective, the Transit Management Center should base the decision to request priority on information collected from the transit vehicle (e.g. location, ridership, etc.) in real-time, most likely through an AVL system. After the Transit Management Center generates the request for priority, this scenario follows the same architecture as Scenario 1. As in Scenario 1, this alternative is most effective when real-time communication connections exist between the Transit Management Center and the Traffic Management Center and between the Traffic Management Center and the local traffic controllers.

One benefit of Scenario 2 over Scenario 1 is that the Transit Management Center maintains responsibility for all decisions to request priority. The central system can weigh inputs from multiple vehicles in the fleet against each other and decide for which vehicles to generate priority requests. However, the demand on the communication system will be heavier under this scenario as every vehicle is passing information to the Center rather than only those that have pre-determined a need for priority, as in Scenario 1.

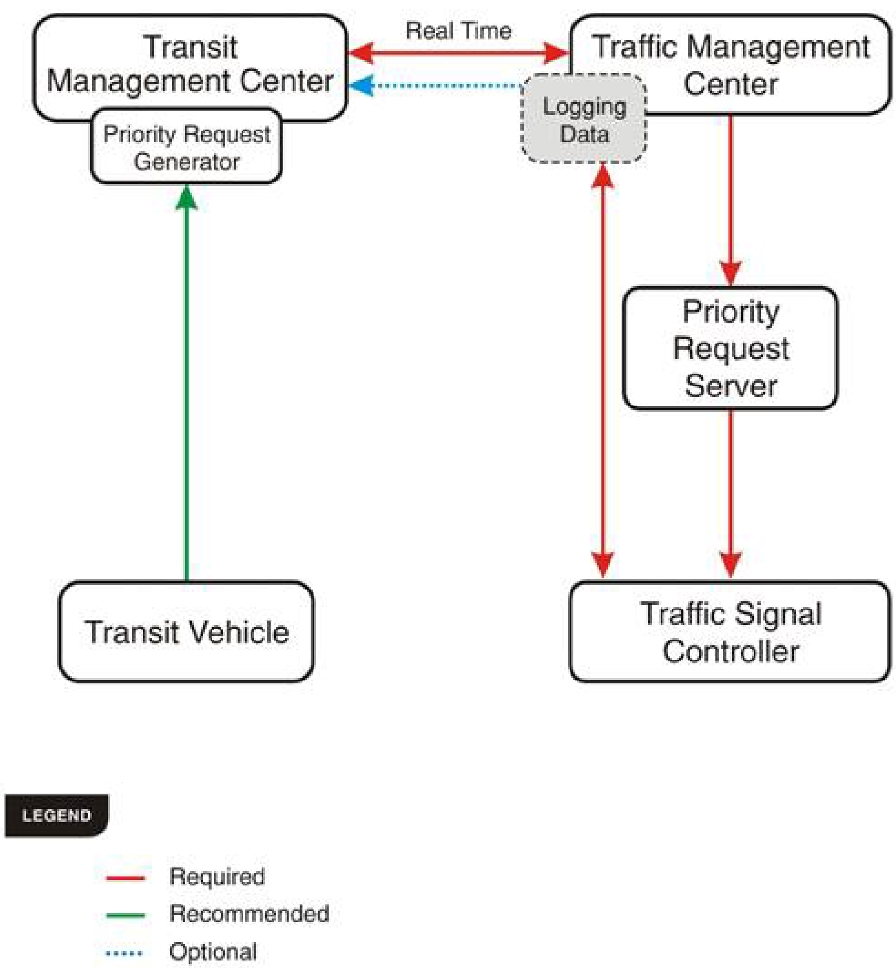


Figure 3-2: Scenario 2 (Centralized)

3.2.1.3 Scenario 3

In cases where the Priority Request Generator is located at the Traffic Management Center the implementation is described as Scenario 3 as shown in Figure 3-3. The information necessary to generate a priority request is channeled to the Traffic Management Center, which contains the processes necessary to determine whether to request priority based on predefined conditions such as schedule adherence, conflicting calls, and ridership. At this point, Scenario 3 becomes very much like the first two centralized scenarios; the priority request is sent to the Priority Request Server, which is located in either the Traffic Management Center or the local traffic controller cabinet.

The actual physical routing of information to the Traffic Management Center may occur in several ways. It is possible that the transit vehicle may communicate with the Transit Management Center, which would then communicate with the Traffic Management Center. A more likely, and efficient, path would be through the local traffic controller to the Traffic Management Center. In this alternative, the fleet vehicle is detected approaching the intersection and the local controller transmits a message to the Traffic Management Center that a transit vehicle is approaching. The Traffic Management Center either communicates with the Transit Management Center regarding schedule adherence of the approaching vehicle or consults information it has locally regarding transit operations. Based upon that information and other traffic information received from the traffic controller, the decision is made whether to grant priority. The updated signal timing parameters are then sent back to the local controller.

Requirements of Scenario 3

Just as in the other centralized scenarios, the key aspect to the effectiveness of this system is the communication infrastructure. It is imperative the communications between the signal controller, the Traffic Management Center, and the Transit Management Center, if involved, happen in a second-by-second fashion, or else communication latency will result in an inefficient priority system.

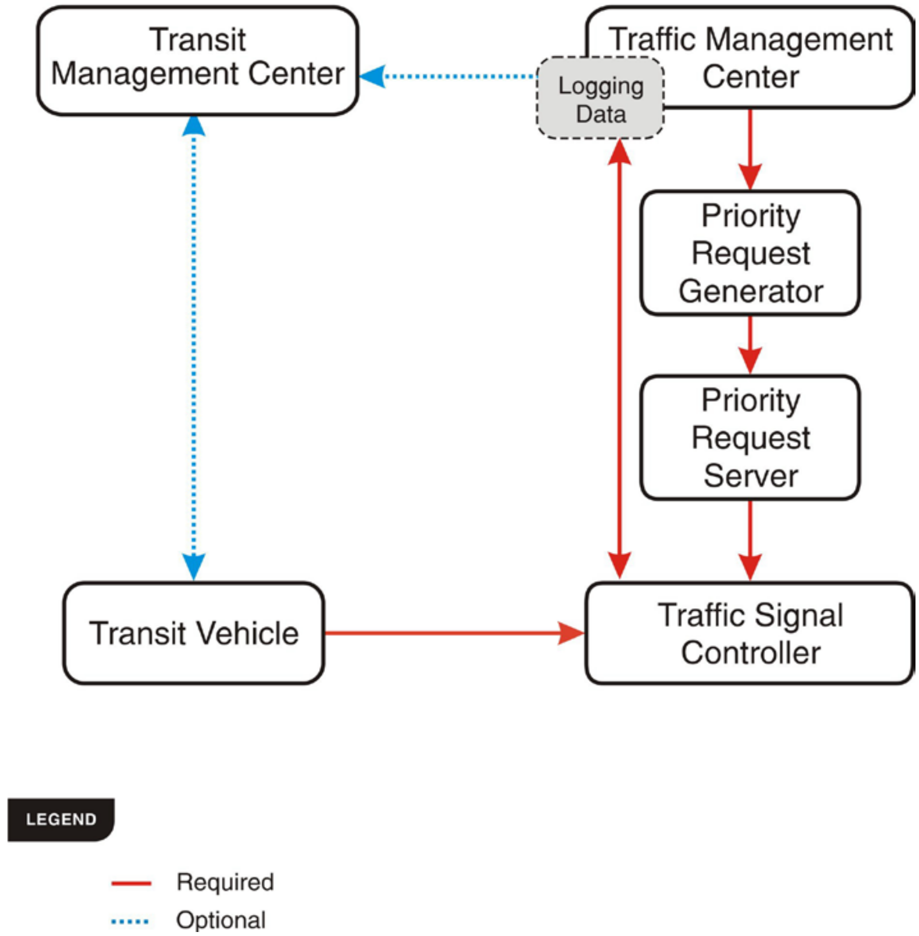


Figure 3-3: Scenario 3 (Centralized)

3.2.2 Distributed TSP Architecture

A distributed priority system does not involve either a Transit Management Center or a Traffic Management Center in the decision making process. All decisions to request and grant priority are made at the local intersection level. This system is advantageous in systems where there is no communication to a Transit Management Center and/or Traffic Management Center or where communication to a center does not occur in real time. This section describes the NTCIP 1211 scenario that has been developed for implementing a distributed priority system and the hardware and communication requirements necessary. A variation of the distributed scenario, Scenario 5, has been proposed by the Transit Communications Interface Profiles (TCIP) Working Group and is included in this section.

3.2.2.1 Scenario 4

The first distributed priority system alternative, Scenario 4, is represented in Figure 3-4. The defining characteristic of this alternative is that the transit vehicle contains the systems and processes necessary to determine whether to request priority based on predefined conditions: schedule adherence, on-route, doors closed, ridership, etc. In addition, the vehicle is capable of sending a NTCIP 1211 compliant message directly to the Priority Request Server requesting priority.

Requirements of Scenario 4

If generation of the priority request is conditional upon schedule adherence, the on-board AVL system needs to be integrated with the fleet vehicle schedule. This is accomplished on-board the vehicle with the AVL system comparing its location to time points in the schedule. The schedule potentially could be uploaded to the vehicle daily via a wireless local area network (LAN) at the garage or via the radio system. Once the vehicle is behind its schedule by a predefined threshold, the priority system is activated. This type of system does not require real-time communication between the transit vehicle and the Transit Management Center or a center-to-center connection between the Transit Management Center and the local jurisdiction's Traffic Management Center.

Under this scenario, individual traffic controllers receive a priority message from the transit vehicle via the detection hardware located at the intersections. The priority message is transmitted from the street detector to the signal cabinet, where the priority request is granted and the signal timing parameters are adjusted.

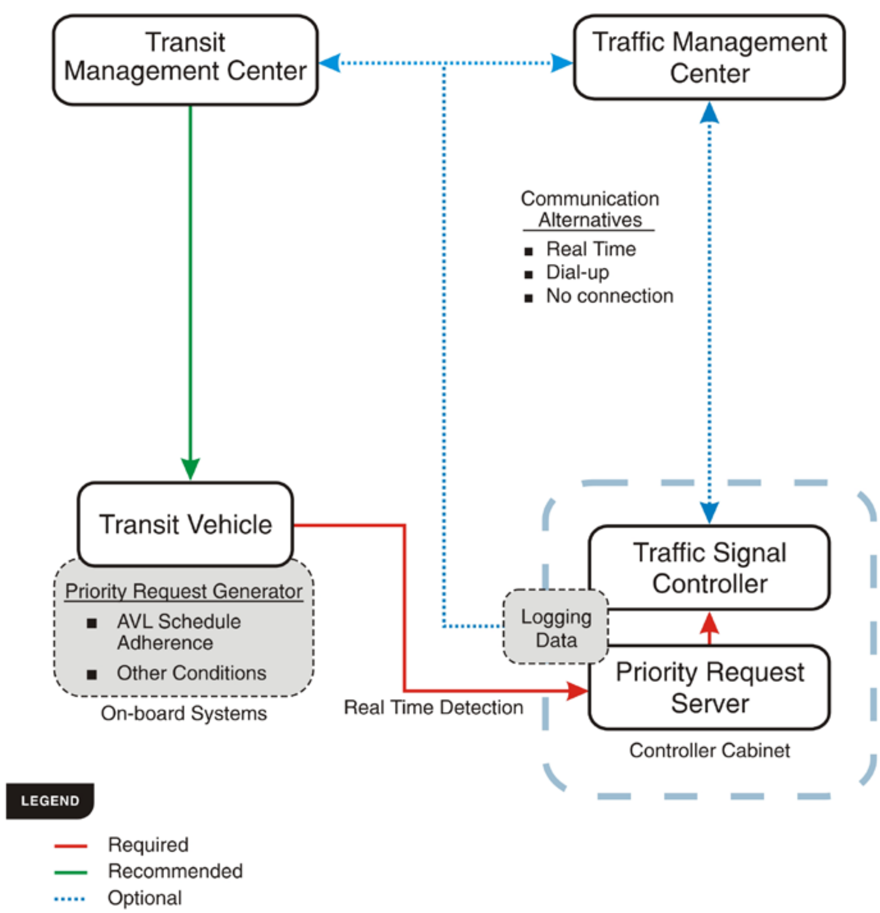


Figure 3-4: Scenario 4 (Distributed)

The Scenario 4 distributed priority system will work regardless of whether a signal system is centralized, closed loop, or isolated, because the ability to request and serve priority rests within the transit vehicle and the local controller, respectively. This is beneficial in a region that is comprised of multiple traffic jurisdictions, some of which may be in a centralized traffic control system and some of which may not.

There are some limitations with this type of system. If a center-to-center connection between the Transit Management Center and the Traffic Management Center does not exist, real-time feedback from the local controller to the Transit Management Center may not be available. The feedback may be necessary to inform the transit agency whether the priority system is active and granting priority and which vehicles are being granted priority. It could also identify how frequently priority is being granted at certain locations. This information could then be used when adjusting schedules of a specific route.

3.2.2.2 Scenario 5

The second distributed priority system alternative, Scenario 5, is represented in Figure 3-5. The defining characteristic of Scenario 5, which differentiates it from Scenario 4, is that the transit vehicle is not responsible for generating a NTCIP 1211 standard priority request. Instead the vehicle conveys a message to the traffic signal system, which contains the Priority Request Generator. The decision to grant priority is also made within the traffic signal cabinet in a Scenario 5 implementation.

Implementation of TSP under Scenario 5 has occurred in at least two different configurations around the country. King County Metro, located in the Seattle metro area, is the most true to form implementation of Scenario 5. Under the King County implementation, the vehicle has an Automated Vehicle Identification (AVI) system, which transmits information, such as a vehicle’s ID number, to a roadside reader. The reader detects the presence of a transit vehicle approaching the intersection and sends a message to a transit interface unit located in the individual signal controller cabinet. Although King County is not currently using schedule-based conditional priority, the interface unit could contain schedule, route, run, and trip information and utilize the AVI information obtained from the transit vehicle to request and grant priority. Under this configuration, the decision to request priority is made solely within the controller cabinet.

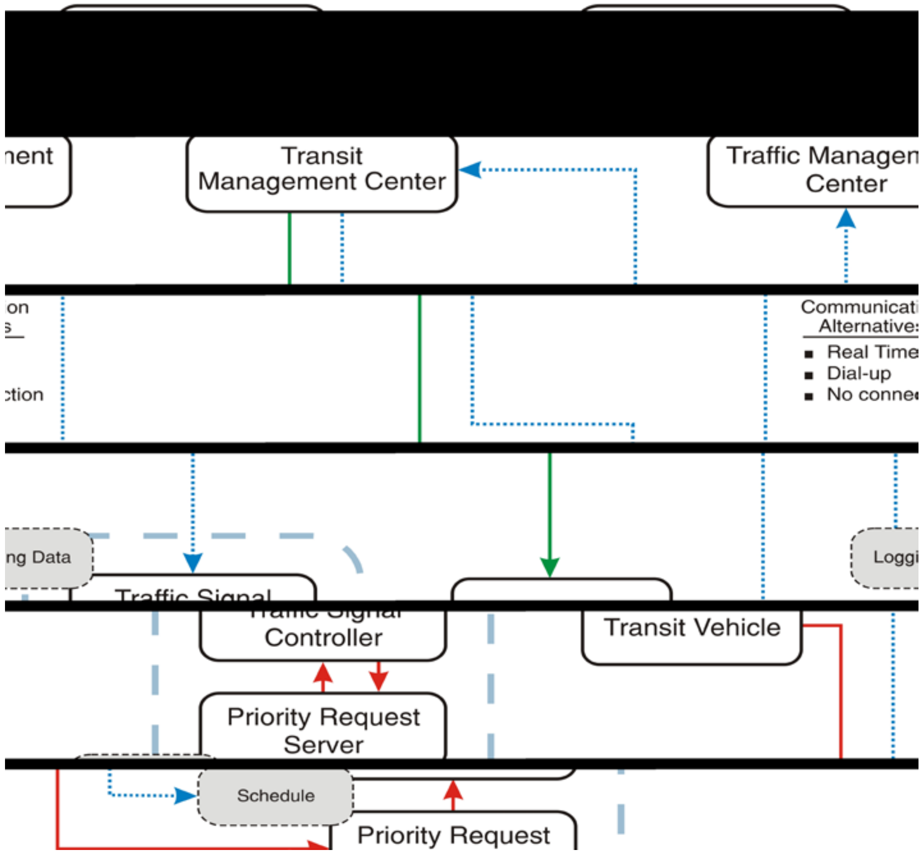


Figure 3-5: Scenario 5 (Distributed)

The transit vehicle is simply communicating its presence approaching the intersection. This type of system has the ability to compare simultaneous conflicting priority/preemption calls and grant priority to the vehicle that has the highest need, an emergency vehicle or a bus behind schedule by a greater amount, for example.

A second configuration of Scenario 5 is the one implemented in Portland, OR. This configuration is actually a hybrid of Scenario 4 and Scenario 5. The information necessary to make a decision whether or not to request priority (e.g. schedule, ridership, etc.) is located on the transit vehicle. However, the vehicle is equipped with detection equipment (e.g. optical-based) that is unable to transmit a NTCIP 1211 standard message. Therefore, the transit vehicle is only transmitting an input to the signal control system when it is in need of priority. The hardware in the controller cabinet is actually generating the standard request for priority. In this configuration, the Priority Request Generator can be thought of as spanning both the vehicle and the controller cabinet. One limitation of this configuration is that the signal controller, because it does not have direct access to information such as operating schedule, cannot weigh requests from multiple vehicles against each other. This generally results in a “first in, first out” operation where the first vehicle to transmit a need for priority is serviced first regardless of relative need.

Requirements of Scenario 5

Real-time communication between the Transit Management Center and the vehicle is not necessary for Scenario 5 to operate. Furthermore, real-time communication between the individual traffic signal controllers and either of the Centers is not required for implementation of this scenario. However, some type of communication connection is required between the transit operating agency and either the individual signal controller cabinets or the transit vehicle fleet. In configurations similar to King County and where schedule-based conditional priority is to be used, a connection is necessary between the controller cabinet and the Transit Management Center to update the transit vehicle route and schedule information in the interface unit located in the cabinet. The interface unit may also have the ability to send AVI tag and operational data back to the Transit Management Center. This connection can be accomplished by different means: fiber, dial-up modem, or wireless. Although much less efficient, this connection could even consist of a technician uploading the transit information to each individual controller cabinet. In the case of an implementation similar to the City of Portland, some communication must exist between the transit vehicle and the Transit Management Center in order to update schedule information. Just as in Scenario 4, the schedule could be uploaded to the vehicle via a wireless LAN at the garage or via the radio system.

The limitations and benefits of Scenario 5 are similar to those of Scenario 4. Because feedback from the local intersection to the management centers may be limited, monitoring of the TSP system may not be possible or efficient. However, the benefit of this scenario is that it can be applied in regions with a variety of signal systems: isolated, closed loop and/or centralized.

3.3 Applicability of SCP Scenarios under different TSP Applications and Operating Policies

The five SCP scenarios provide an opportunity to deploy TSP under a variety of frameworks. As such, there is the opportunity to apply the scenarios in various operating environments and with differing objectives. This document provides an assessment of these various applications for the different scenarios.

Many of the current TSP implementations rely on little more than transmitting a vehicle's presence at the intersection or, at most, an identification number. The information is then used to initiate a different sequence of signal timing, presumably providing an advantage to the requesting vehicle while remaining in coordination with adjacent traffic signals. These priority strategies are different than the traditional preemption system, which would terminate non-priority phases and then hold the green for the requesting vehicle. The NTCIP 1211 standard creates a standardized message set with the intent of moving beyond a "contact-closure" system. Table 3-1 identifies the message objects that are passed from the PRG to the PRS in an NTCIP 1211 TSP implementation.

Table 3-1: NTCIP 1211 Objects - PRG to PRS Message

Object	Function
PriorityRequestID	Unique identifier assigned by the PRG to identify a particular priority request
PriorityRequestVehicleID	Unique identifier for vehicle (typically VIN)
PriorityRequestClassType	Relative priority of request on scale of 1- 10 (1=highest, 10=lowest)
PriorityRequestClassLevel	Relative priority within each class on scale of 1- 10 (1=highest, 10=lowest)
PriorityRequestServiceStrategyNumber	PRG requested strategy
PriorityRequestTimeOfServiceDesired	Estimated time of arrival at the intersection
PriorityRequestTimeOfEstimatedDeparture	Estimated time of departure from the intersection

The standard NTCIP message does not include information such as vehicle location, direction of travel, speed, occupancy, or schedule adherence. This was done to simplify and standardize the information exchange under the assumption that "smart" priority request servers would determine the priorities for their fleet. As will be explained in the following sections, depending on the SCP scenario and desired operation, it may be necessary to pass more information than what is required in the standard message. The following sections discuss the application of each of the SCP scenarios under various physical and operational environments.

3.3.1 Unconditional Priority Requests

In an unconditional priority system, a request for priority is made each time an eligible transit vehicle approaches an intersection. A TSP request is issued regardless of any existing conditions (e.g., schedule adherence, passenger loading). Although unconditional priority permits a fairly simple path to implementation, there are some drawbacks.

Drawbacks

One of the most apparent risks associated with unconditional priority is providing priority to a vehicle that is on time or ahead of schedule. Schedule reliability is an important factor in rider satisfaction, and a bus leaving a scheduled timepoint ahead of schedule can cause frustration among riders who miss their bus as a result. When priority is provided regardless of a vehicle's current schedule adherence, the risk of vehicles running ahead of schedule, and causing such inefficiencies as bus bunching, is increased.

A second risk associated with unconditional priority is giving priority to a vehicle that is not currently on an active route[1]. For instance, a bus returning to the garage at the end of a scheduled run would request priority despite not being in active service. As a result priority may be provided for a bus that has no passengers and no need for priority to the

[1] A transit agency that is attempting to reduce costs may argue that by providing priority to non-revenue buses this goal is achieved. One might suggest that during periods of low traffic that priority is worthwhile.

detriment of traffic or even buses making opposing movements. The King County (Seattle, WA) TSP implementation addresses this issue by requiring a message that contains the vehicle's current route and run number. A transit interface unit at each intersection compares the information in this message to a stored database and determines whether the requesting vehicle is currently on route and in active service. Although the current King County system is considered unconditional in the sense that it does not determine the need for priority based on schedule adherence, it does confirm that the requesting bus is a valid and in-service bus.

The following sections provide a brief overview of the implementation of unconditional TSP by scenario.

3.3.1.1 Scenario 1: Centralized, Transit Vehicle Generates Request

Under Scenario 1, the transit vehicle is responsible for sending a priority request to the Fleet Management Center, which then forwards the request to the traffic signal system via the Traffic Management Center. If no conditional processing of that request is going to occur (e.g., schedule adherence), there may be no reason to implement TSP under a Scenario 1 configuration. The routing of a request through a central system would provide no benefit, beyond monitoring capabilities, and may introduce additional latency into the process. It is possible, however, that the only means of communication to the local intersection is through the central system.

3.3.1.2 Scenario 2: Centralized, Transit Management Center Generates Request

The Transit Management Center is responsible for generating a priority request under this scenario. In an unconditional priority application, the necessary information at the Transit Management Center would include the vehicle's current location and heading. This information would be updated as the bus approaches the intersection to allow the center to provide priority. If the transit vehicle is communicating in real-time to the management center through a CAD/AVL system[2], then this connection already exists. However there may be a need for additional information that is more operations oriented to be sent from the vehicle to the central system.

3.3.1.3 Scenario 3: Centralized, Traffic Management Center Generates Request

In an unconditional priority application, this scenario functions the same as Scenario 2. The primary difference is that the PRG is located at the Traffic Management Center. Therefore, the information necessary to generate an NTCIP message must be available at the Traffic Management Center, either through information stored at the Traffic Management Center or passed from the local intersection or through the Transit Management Center.

[2] Implementation of a system of this nature is rarely seen in the U.S. The AVL system implemented by Montgomery County, Maryland had this capability during its initial pilot study, but expansion of the system has limited the data transmitted.

3.3.1.4 Scenario 4: Distributed, Transit Vehicle Generates Request

Under Scenario 4, the transit vehicle is responsible for generating an NTCIP message and communicating that request directly to the local intersection controller. If the desired strategy is to request priority immediately when the vehicle enters the detection range, there may be no need to have the TSP system integrated with an AVL system. However, if the NTCIP message is to include estimated times of arrival and departure, the TSP system may need to be integrated with an AVL system or other on-board GPS equipment.

3.3.1.5 Scenario 5: Distributed, Signal System Generates Request

In an unconditional priority implementation, Scenario 5 is very similar to Scenario 4. The only difference is that the standard NTCIP message is generated on the roadside under Scenario 5. If estimated times of service and departure are to be used, the vehicle must transmit information regarding current location, speed, and heading to the roadside system where the PRG is located.

3.3.2 Conditional Priority Requests

While unconditional TSP will improve average travel time, reliability of transit service is not likely to improve and may even decrease as a result of vehicles running ahead of schedule. Also, unconditional TSP is essentially a first come, first serve process. Consequently, conditional priority requests considering route schedule adherence and other criteria may maximize the benefits of TSP. Additional information, such as on-board passenger counts[3], may also be used to generate a conditional priority request. Applying conditional priority based on the relative needs of the transit vehicle can result in a more balanced application of TSP. This is best done at the fleet level where the overall picture of competing requests can be processed.

The information exchange required for a conditional TSP system will vary by scenario. The following sections describe some general considerations related to conditional priority for each scenario. Additional detail on applying TSP according to specific conditional parameters is provided in later sections. The conditional priority system implemented by TriMet in Portland, Oregon is shown in

Figure 3-6. Following implementation of these conditions, there were several additional considerations added such as inclusion of the stop requested bell on board, turn signal activation, and several other elements that the engineer could use to design an effective priority system.

[3] The application of TSP using passenger counts represents a policy that is favorable to person movement and may not meet the goals of reducing the transit agency operating costs.

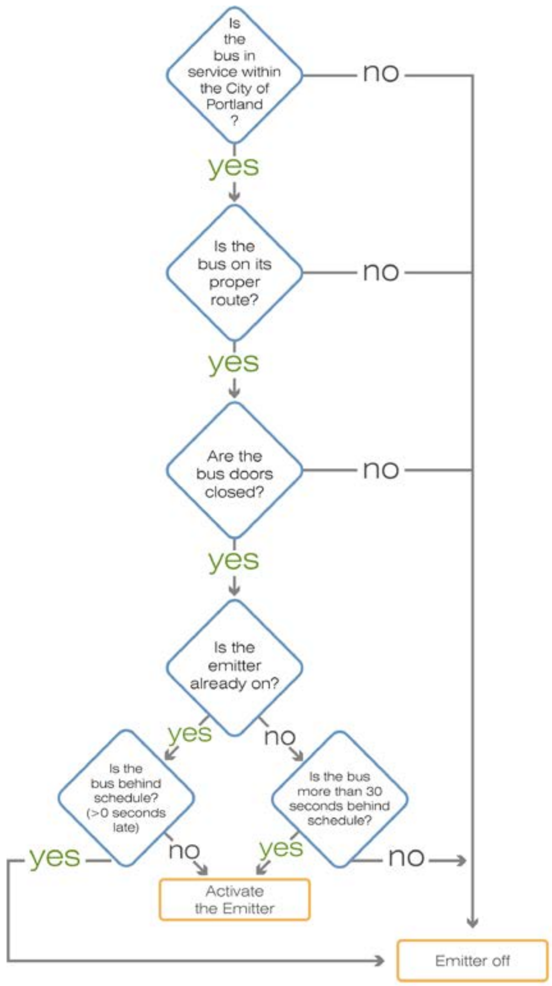


Figure 3-6: City of Portland Conditional Priority Request Process

3.3.2.1 Scenario 1: Centralized, Transit Vehicle Generates Request

As shown in Table 3-1, the standard NTCIP 1211 message from the PRG to the PRS does not include absolute measures, such as amount of lateness or vehicle occupancy that could be used to make a conditional priority request. Because the decision to request priority must be made by the PRG on the vehicle under a Scenario 1 implementation, the on-board system must be capable of gathering and evaluating the information necessary to generate a conditional request.

If route schedule adherence is to be considered, data from the AVL system must be incorporated into the process, or the PRG must be capable of knowing where the vehicle is in relation to its scheduled location. If a conditional request is based on passenger loading, the PRG must interface with the automatic passenger counter (APC).

The information gathered by the PRG must then be processed in order to make the decision to request priority or not request priority. The PRG will generate and send a request only if a predefined threshold (e.g., amount of lateness or number of on-board passengers) has been met. Alternatively, a message could still be generated and sent if the threshold is not met, but the Service Strategy object, Priority Request Service Strategy Number, would be set to a value that the PRS recognizes as a non-service value. This would enable monitoring of the TSP system and verification that requests are being generated.

3.3.2.2 Scenario 2: Centralized, Transit Management Center Generates Request

For a conditional request to be made under a Scenario 2 implementation, the same information needed for an unconditional request (i.e. location, heading, speed, etc.) must be sent to the Transit Management Center. In addition, the transit vehicle must have a method of communicating the necessary information for making a conditional priority decision. For instance, if the priority request is to be based on vehicle occupancy, it would be necessary for the vehicle to transmit passenger loading information to enable the center to evaluate the information and make a decision to request priority or not.

3.3.2.3 Scenario 3: Centralized, Traffic Management Center Generates Request

Under a Scenario 3 implementation, the Traffic Management Center will receive notification of a transit vehicle in need of priority service either directly from the vehicle via the local intersection or from the Transit Management Center. In this configuration, the central traffic system will know for which intersection approach priority should be provided. If the estimated time of service and departure are based on a predefined detection distance and an assumed speed and the message is sent from the local intersection, it may not be necessary to send anything beyond the transit vehicle's identification number. This is assuming that the central system is able to use the vehicle's identification number to make a conditional priority decision. However, if additional information, such as passenger loading, is to be used in the priority decision making process, that information will also need to be passed to the central system.

Although it is not based strictly on NTCIP 1211 messages, the Los Angeles Department of Transportation (LADOT) system in the City of Los Angeles follows this configuration. Figure 3-7 details the components and flow of information in the LADOT TSP implementation. As shown in the figure, the fleet vehicle is detected at a fixed location on the street (via an inductive loop) and passes an ID number to the local controller. The controller passes this information along with the detector and controller status to the Transit Priority Manager (TPM), which is located at the Traffic Management Center. In a parallel process, the controller is also communicating with the central Adaptive Traffic Control System (ATCS) for the regular timing functions. The TPM checks the headway schedule and makes a decision whether or not to request priority. If priority is requested, a message is sent back to the Transit Priority System (TPS) in the local controller. The TPS communicates within the controller with the Traffic Signal Control Program (TSCP) through a shared memory data module. The local controller will override a request for priority if priority was granted in the previous cycle. When a request for priority is granted the connection between the TSCP (local) and ATCS (central) goes offline and the local controller makes timing decisions until the controller is no longer in priority mode.

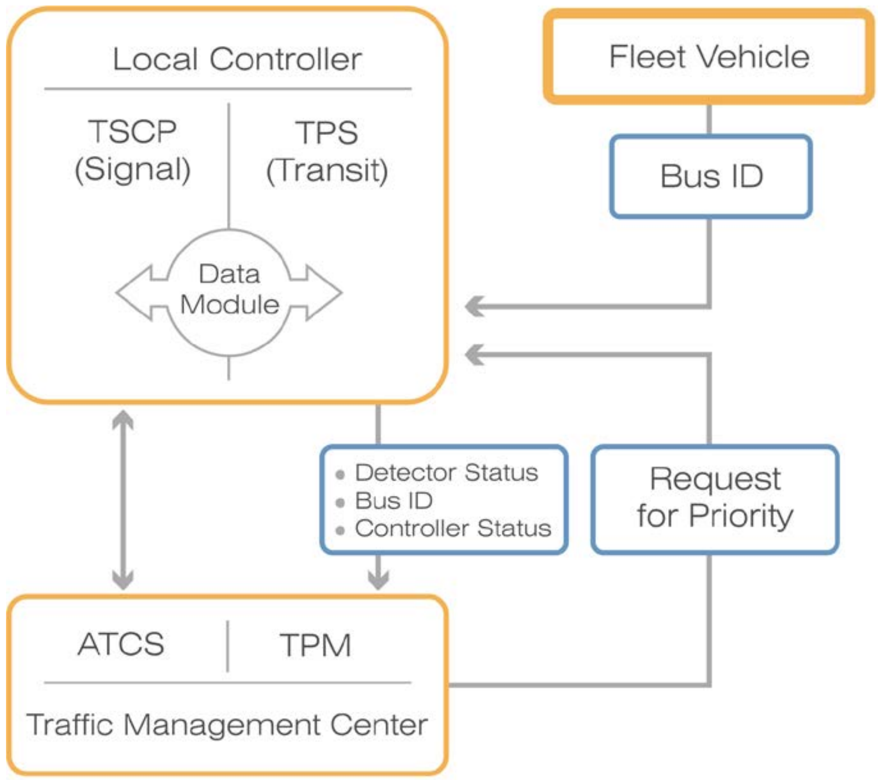


Figure 3-7: LADOT Centralized TSP System

In order for the LADOT system to conform to the NTCIP 1211 standard, the central system would need to be capable of calculating an estimated time of service and departure at the intersection. In this case, the check-in message is sent at a pre-determined distance from the intersection. If a vehicle speed is assumed, an estimated time to service could be calculated.

3.3.2.4 Scenario 4: Distributed, Transit Vehicle Generates Request

A conditional priority implementation under Scenario 4 requires that the transit vehicle be capable of generating an NTCIP message based on the desired conditions and communicate that request to the local controller. Therefore, the vehicle's on-board equipment must be capable of gathering and processing information related to the conditional parameters (e.g., schedule adherence, vehicle occupancy).

The Portland TSP implementation is an example of conditional priority being applied in a manner similar to a Scenario 4 implementation. The Portland example is not a strict NTCIP implementation because the bus does not communicate an NTCIP standard message. However, the bus does evaluate the need for priority based on schedule adherence by comparing its current location to a schedule database stored on-board. If the bus determines that it is behind schedule by some predefined threshold, it activates an optical emitter, which is used to check-in at each intersection. If the Portland deployment was modified to utilize technology capable of transmitting an NTCIP message, it would operate as a Scenario 4 implementation.

3.3.2.5 Scenario 5: Distributed, Signal System Generates Request

Under Scenario 5, the decision to request priority is made by a PRG external to the vehicle (e.g., roadside cabinet). Therefore, the information necessary to make a conditional request must be either communicated from the vehicle to the roadside (e.g., schedule adherence, passenger loading) or stored in a roadside interface unit (e.g., schedule adherence using a stored database).

The previously mentioned King County implementation utilizes an interface unit within the roadside cabinet. This interface unit references a stored database to confirm that vehicles that have checked into the intersection are on a valid route. Although the current system does not use schedule adherence to generate a conditional request, the roadside interface unit could contain a schedule database that would be referenced to determine if a particular vehicle was behind schedule. This may require frequent updates of the database to accommodate schedule changes.

3.3.3 Prioritizing Multiple Requests

As agencies expand the use of TSP, it will become increasingly likely that two or more transit vehicles will approach an intersection concurrently and result in conflicting calls for priority. The PRS, whether located in a central location or at the roadside, must then decide which vehicle will be given preference. Historically, most TSP implementations have not been capable of determining the order in which individual requests should be served. The result has generally been a first-in/first-out (FIFO) scenario, where the first vehicle requesting priority is serviced first. Depending on the operating policy, the next vehicle may or may not get priority in the following cycle.

The LADOT TSP software is currently configured such that if competing calls for priority are received from crossing lines, the line on which TSP was first implemented will receive preference. Although not incredibly sophisticated, this method provides a consistent determination of which line will receive preference. In the case of the LADOT, TSP was first implemented for the Metro Rapid service. Therefore, a Metro Rapid line would receive preference over a conflicting call from a local service bus for which TSP was implemented at a later date.

Use of the NTCIP 1211 object set permits prioritization of conflicting calls using two objects: PriorityRequestClassType and PriorityRequestClassLevel. As previously outlined, the PriorityRequestClassType function allows a relative class ranking of requests while the PriorityRequestClassLevel defines further ranking within each class. Because the standard message contains no object for defining absolute values such as amount of lateness or vehicle occupancy, the PRG must be able to translate these absolute numbers into relative values, which can be used by the PRS to weigh multiple requests against each other. For example, if passenger loading is used as the conditional parameter for determining relative preference, the class level could be set according to the number of passengers on the vehicle (e.g., Level 1: >50 passengers, Level 2: = 40-49 passengers, etc.). In this case, a bus with a Level 1 would receive preference over a bus with Level 3. However, an LRT vehicle, which is harder to bring to a stop, could always be given priority over a bus regardless of passenger loading by setting the class type to a preferred value (e.g., LRT = Type 1, BRT = Type 2, Local Bus = Type 3, etc.).

3.3.3.1 Scenario 1: Centralized, Transit Vehicle Generates Request

With the PRG on the bus, as is the case under Scenario 1, the on-board equipment would be responsible for determining the class type and level based on predefined thresholds. The on-board PRG would use information, such as degree of lateness or percent occupied, to set the relative class type and level objects within the standard message set. The PRS would then receive these objects as part of the message, compare the values to those of competing requests, and grant priority to the request with greater preference.

3.3.3.2 Scenario 2: Centralized, Transit Management Center Generates Request

Under a Scenario 2 implementation, the information required to be transmitted from the bus to the Transit Management Center depends on the capabilities of the center and the parameters being used for determining relative priority. If the parameter being used to set the relative priority is degree of lateness and the central CAD/AVL system is capable of monitoring schedule adherence and vehicle location in real-time, then the vehicle may not need to transmit any additional information. However, if passenger loading is being used to determine preference, it would be necessary for the vehicle to transmit information from the on-board passenger counters to the central PRG, which would then determine the class type and level.

3.3.3.3 Scenario 3: Centralized, Traffic Management Center Generates Request

The primary difference between Scenario 2 and 3 is that the PRG under Scenario 3 is located at the Traffic Management Center, which may not be capable of determining information such as degree of lateness. Therefore, this information would need to be included in the check-in message from the transit vehicle. Alternatively, the check-in message could be routed through the Transit Management Center, which would add the necessary information to the message.

3.3.3.4 Scenario 4: Distributed, Transit Vehicle Generates Request

In this case, Scenario 4 operates much the same as Scenario 1. The on-board PRG is responsible for determining class type and level. The difference under Scenario 4 is that the message is communicated directly to the PRS at the local intersection rather than through the central system. In order to adequately assess competing calls for priority, it may be necessary to communicate the message to the PRS well in advance of the intersection. This may preclude some check-in detection technologies.

3.3.3.5 Scenario 5: Distributed, Signal System Generates Request

Under Scenario 5, the vehicle would need to transmit the information necessary to complete the class type and level to the roadside PRG. This information may include type of vehicle and service (e.g., LRT, BRT, etc.), passenger loading and/or schedule adherence.

3.3.4 Operating Policy: Schedule vs. Headway Based

The applicability of the SCP scenarios will vary depending upon the operating policy for a particular route. The two primary operating policies are schedule-based and headway-based. This section compares and contrasts conditional priority under these two operating policies. The differences are discussed in general terms and focus more on the location of the PRG rather than the specific requirements for each of the five scenarios.

3.3.4.1 Schedule-Based

The goal of conditional priority based on maintaining a published schedule is to have transit vehicles arrive at scheduled timepoints as close as possible to the published time. Therefore, it is desirable to give priority to vehicles running behind schedule in order to achieve schedule adherence. Conversely, it is detrimental to provide priority to a vehicle that is on time or ahead of schedule. As previously explained, a transit vehicle running ahead of schedule reduces the reliability of service for passengers.

On-Board PRG

Those scenarios under which the PRG is located on board the vehicle (i.e. Scenarios 1 and 4) require that the vehicle be capable of determining not only its current location but also its scheduled location at the time. Often referred to as a “smart-bus”, a vehicle capable of determining its schedule adherence is most often equipped with a GPS-enabled AVL system. Schedule information is either stored on-board or communicated to the vehicle in real-time from a central system.

If the information is stored on-board but vehicles are not consistently assigned to the same route each day, an efficient method for updating the schedule information on each vehicle at the beginning of each operating day will be required. Some agencies are able to perform this function using the data bandwidth available on the existing radio system. However, some existing systems are constrained by available bandwidth or on-board memory and cannot efficiently upload schedule information each day. Therefore, a dedicated process may be required for uploading schedule information to the vehicle. Another option is for the system to update the schedule at timepoints or connections with “hot spots.” TriMet has considered using its fiber backbone at light rail stations to update relevant information and make real-time operational decisions related to bus operations.

Assuming that the vehicle is capable of determining compliance with the schedule, the process for issuing a conditional message is relatively straightforward. The on-board PRG issues a request only when the conditional priority requirements have been satisfied. Ideally, the PRG would also include class type and level object information in the message sent to the PRS.

External PRG

In the case of a PRG external to the vehicle, the location of the PRG is an important consideration. If the PRG is located at the Transit Management Center (Scenario 2) and the center is monitoring each vehicle’s schedule adherence in real-time, then the center can communicate the necessary information directly to the PRG.

However, if the PRG is located within the signal system, either at the Traffic Management Center (Scenario 3) or at the local intersection (Scenario 5), the need for priority based on schedule adherence information must be relayed to the PRG, either by the vehicle or the Transit Management Center. If the PRG is responsible for making the conditional decision, then this information will consist of raw data (e.g., vehicle ID and location) and the PRG will need to consult a schedule database to determine schedule adherence. Maintaining updated transit schedule information at either the Traffic Management Center or at the local intersection may be the most challenging aspect of this configuration. It is also possible that the conditional decision may be made prior to reaching the PRG, either by the Transit Management Center or by a “smart-bus”, and the PRG only needs to receive this decision.

3.3.4.2 Headway-Based

Rather than relying on scheduled timepoints, headway-based transit systems aim to maintain a consistent temporal spacing between vehicles. Therefore, applying conditional TSP based on headway maintenance requires that the spacing between vehicles be monitored and known by the PRG. The location of the PRG may be a key determinant in the applicability of TSP in a headway-based system.

On-Board PRG

Given current technology, an on-board PRG will likely pose the greatest difficulty in implementing conditional priority based on headway maintenance. Unlike schedule-based systems, headway-based conditional priority is based on the spacing between the vehicle currently at the intersection and the previous vehicle to pass through the intersection. Therefore, the conditional priority decision is not a discrete decision as it is under schedule-based systems.

Currently, no TSP deployments permit vehicles to communicate to other vehicles. Therefore, in order for a vehicle to know its spacing from the previous vehicle, it would need to receive this information from a central CAD/AVL system. This would require a real-time feedback loop between the transmit management center and individual vehicles.

An alternative method for communicating headway spacing between vehicles could result from the current USDOT initiative to establish vehicle-to-vehicle and vehicle-to-roadside communications. This initiative, known as Vehicle Infrastructure Integration (VII), uses wireless communication to transmit data between individual vehicles and from vehicles to the roadside. Using VII, future TSP implementations would enable vehicles to communicate their temporal and spatial location relative to each other.

External PRG

Headway-based conditional priority using an external PRG is being done today in both LADOT and LA County implementations. The LADOT system utilizes the central TPM computer to monitor the spacing of buses and determine when the desired headway spacing is being exceeded. The LA County system uses a timer within the local controller cabinet to monitor the spacing of buses at each intersection. The timer is reset each time a bus passes through the intersection. A request is generated only when the timer indicates that the defined headway has been exceeded.

4 TSP Technology and Implementations

4.1 TSP Technologies

This section defines the infrastructure necessary for the implementation of a transit signal priority system. The components necessary for a successful implementation of TSP may include:

- Transit Vehicle Detection
- Traffic Signal Hardware and Software
- Transit Vehicle AVL System
- Communication Technology
- Traffic and Transit (Fleet) Management Centers

It is important to note that the role of each component depends on the type of TSP implementation. In some cases, the various components may not be required for implementation. For instance, a distributed system, which will be defined in a later section, does not require communication with either a Traffic Management Center or a Transit Management Center.

A systems engineering process should be undertaken to identify the most appropriate implementation for a specific jurisdiction. The systems engineering process is initiated by developing a concept of operations that identifies the various elements of TSP. The process may require multiple iterations due to the need to consider multiple jurisdictions and components. The system will be defined by the traffic signal system, the detection system, the transportation management centers, and the communication systems that support the data flows between the architecture’s physical entities. In each case, the technical element requires a technology review to assure that the proper standards are employed within the regional architecture and that the components can be successfully integrated across multiple jurisdictions, to the extent practical. Finding and analyzing solutions that meet the concept of operations requires study in each of the following three process areas to select the best candidate solution. An initial overview of the extent of these analyses is provided for review:

- Transit Vehicle Detection (Initiation of Priority Request Process): This is an important element of the scenario assessment. It will be the major focus of the analysis as there are many options to consider, and the decisions have implications for both transit and traffic agencies. The transit vehicle detection technologies that will be considered are AVI loop, optical/infrared, wayside radio frequency (RF) tags, AVL/GPS radio, centralized AVL systems, and Wi-Fi wireless.
- Traffic Signal System: The transit agency’s role with traffic signal control evaluations will be advisory only, due to the degree of the local traffic engineering agency’s responsibilities for maintenance and operations. The traffic signal systems participation consists of various requirements for traffic

management centers and traffic signal controllers depending on the availability of internal and external communications.

- Supporting Systems: Consideration of communications and management center technologies will occur in concert with the overall ITS architecture. These supporting systems are vital in many cases to the monitoring and performance of the system and management of information flows that are defined.

The assessments will address each component's operation, performance, testing, installation, cost and schedule, training, and maintenance needs. The final task will be to prepare an operational concept, implementation plan, and operational testing plan.

4.1.1 Transit Vehicle Detection (Initiation of Priority Request Process)

A transit signal priority implementation requires that the system be able to explicitly detect a transit vehicle and determine the intersection approach for which priority should be granted. While a variety of means are available to initiate the process, most TSP implementations have used special TSP detection systems because existing detection systems do not distinguish between different types of vehicles. The selection of a detection system is an important step in developing a TSP Concept of Operations that can meet the project objectives.

It is important to coordinate the TSP selection process with the traffic agencies as they are typically responsible for maintenance of the TSP components directly integrated into the traffic signal system. It may be advantageous to select a form of detection that corresponds to the existing detection system being used by the traffic agency for emergency vehicle preemption. The type of detection system may also be dependent on the requirements of the TSP software algorithm. Some systems require notification when the transit vehicle has cleared the intersection during the green extension phase so that the extension can be terminated and operation returned to the typical coordination.

The sections below describe the primary detection systems used to institute transit signal priority.

4.1.1.1 AVI Loop

AVI loop detection systems are commonly referred to as "smart" loops, because the technology used distinguishes the transit vehicle from general traffic. These are typically applied with an Automatic Vehicle Identification (AVI) system, which consists of three components. The first component is a coded transmitter attached to the underside of the priority vehicle. The transmitter comes from the manufacturer with an unchangeable, unique identification code for AVI functionality. The transmitter provides an output signal to the second component, an antenna-based vehicle detection system integrated into a loop detector. The loop detector can be either a standard inductive loop for vehicle detection or a loop installed exclusively for transit vehicle detection. If existing loops are used, they must be located far enough in advance of the intersection to permit adequate time for priority to be applied. The last component is a receiver, typically located in the signal controller

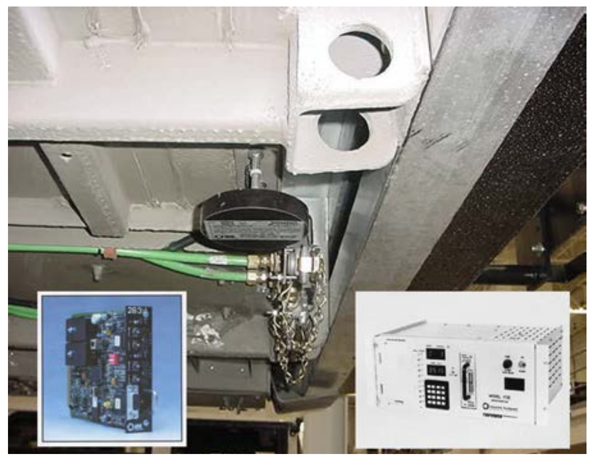
A uniquely coded transmitter is attached to the underside of the transit vehicle.

cabinet. The current generation of AVI transmitters sends only the identification code of the transmitter itself. However, at least one manufacturer is currently developing a system capable of transmitting additional information, such as driver identification.

There are various distributors of AVI loop systems, including Reno A&E and U.S. Traffic's LoopComm. The Reno A&E system is in place in the City of Los Angeles' transit signal priority program, which is operated through a centralized system for vehicle headway management and other data collection. The LoopComm 600 series system is in use on the Cermak Road TSP Corridor in Chicago, Illinois, which is operated as a distributed system.

The advantages of this technology include:

- Similar to conventional loop detection, which contractors are familiar with installing (reduced installation costs).
- Ability to provide "check-out" function if an additional detector is provided. Check out detection may provide "check-in" at closely spaced intersections.
- Short communication range between transmitter and detection loop reduces potential for false or missed calls.
- Proven technology that works in all weather conditions and detects all vehicle types.



The AVI system as installed under a bus in Los Angeles County, California (Photo Credit: VTA, San Jose, CA)

- Low cost transmitters on each bus reduces overall system cost.

The limitations of the technology include:

- Requires loop detectors to be appropriately placed at the time of installation, not flexible with regards to adjusting detection location after initial placement.
- Communication from bus to signal is only an identification code (current generation of AVI).
- Loop detectors are subject to failure due to pavement flexing or being cut during roadway construction activities.

4.1.1.2 Optical/Infrared (light-based) detection

Light-based detection is currently the most common system used for both TSP detection and emergency preemption. An optical/infrared system consists of three components: (1) emitters on the vehicles, (2) detectors mounted at or near the intersection, and (3) a phase selector in the controller cabinet that implements the request for priority or preemption.

An optical emitter as installed on a bus in Portland, OR. (Photo Credit: Peter Koonce)

The optical emitter is typically located at the front atop the vehicle and can be activated manually by the driver or by some automatic method. When activated, the emitter sends a pulsating signal in both the visible and infrared wavelengths to the detector located at or near the intersection. The detector is typically mounted on the signal mast arm or span wire at the intersection but may also be mounted in advance of the intersection if there are line-of-sight obstructions on the approach to the intersection. The infrared signal sent by the emitter contains an identification code. The detector at each intersection receives the signal from the transit vehicle and routes it to the phase selector, which validates the priority request and provides an input into the signal controller.

The advantages of a light-based (optical/infrared) detection system include:

- Can be used simultaneously by both emergency service providers and transit vehicles.
- Optical detectors are already installed at many intersections around the country.
- Variable detection point settings allow flexibility in setting the range for priority requests.
- In-cabinet technology that logs priority requests and requires little customization of traffic controller cabinets.
- Field-tested and proven technology.

The limitations of a light-based (optical/infrared) detection system are:

- Requires line of sight between the emitter and detector.
- Latency in receiving requests from optical emitter may occur due to range acquisition.
- Limited accuracy of detection range setting because of the optical detection.
- Data transfer is limited to an identification code.

- Limited number of identification codes.
- Higher costs (as compared to most systems), especially when large numbers of intersections are desired for TSP.
- Each bus would need to be equipped with optical emitters (new piece of equipment).

There are various distributors of the optical based TSP detection system. The most widely deployed is the 3M Opticom system, but the Optronix/Tomar Strobecom system is also used in select communities throughout the country.

4.1.1.3 Wayside reader detection

The wayside reader-based detection varies quite a bit among system vendors. Most commonly used for highway tolling systems, these readers have not seen much use in the transit industry. Only Seattle's King County Metro has implemented a wayside reader-based detection system for their TSP operations. As illustrated in Figure 4-1, this detection system consists of three parts: 1) a vehicle mounted RF transmitter, 2) a wayside reader, and 3) a priority interface device. As the bus approaches an intersection, the transmitter sends a radio signal to a wayside receiver mounted on a roadside pole upstream of the intersection. This wayside receiver then relays the signal to a priority interface device located in the traffic control cabinet in a distributed system or forwards the message on to a traffic and/or transit management center in a centralized system to determine if and how much priority should be granted.

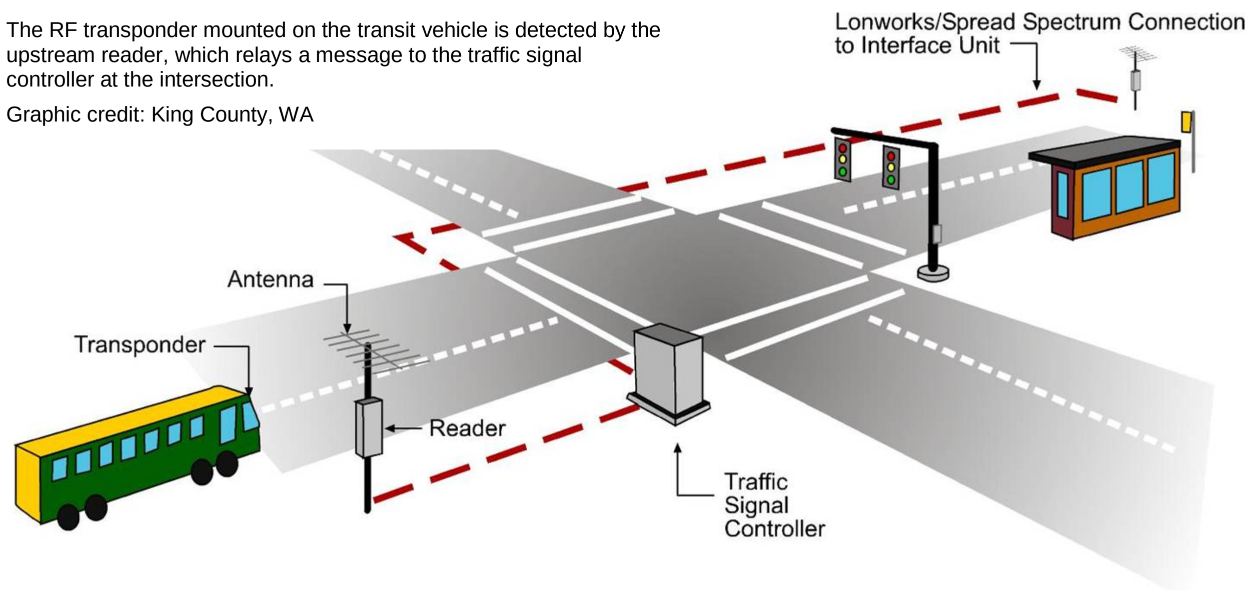


Figure 4-1: Wayside Reader Detection

The advantages of a wayside reader-based detection system are:

- Line of sight and visibility are not required for detection.
- Systems offer check in/check out capabilities provided two wayside detectors are installed.
- Non-intrusive detection that requires no modification in the roadway.

The limitations of a wayside reader-based detection system are:

- Requires suitable curbside mounting locations upstream of the intersections for the tag readers and communications.
- Not easily applied within a centralized system due to separate system for management of the ID system as implemented within the King County system.
- Challenges with integrating into existing transit systems, such as AVL or scheduling.
- Higher hardware costs and may require licensing fee.

Examples of the wayside reader detection system include McCain Traffic's AVI system and Transcore's Amtech RFID system.

4.1.1.4 Global Positioning System (GPS) and Radio-based Communications

Distributed, AVL-based Systems

The GPS and radio-based communication system relies on GPS receivers mounted on the emergency vehicle or transit vehicle to determine vehicle position, direction, speed, and time of day. This information is used to determine the appropriate preemption or priority request and activity. Communication from the vehicle to the signal controller is achieved by means of radio transmitters on the vehicle and receivers at the intersections. This is a system that was recently developed by 3M and has limited implementation throughout the country.

The advantages of the GPS and radio-based communication systems are:

- Wireless communications greatly reduce infrastructure costs to implement TSP.
- Line of sight and visibility are not required for TSP detection.
- Potential to utilize the same system equipment on both emergency and transit vehicles for preemption and priority routines.
- Potential to transmit large amounts of data via radio, especially in conjunction with AVL, APCs, and other transit ITS systems.
- Systems potentially offer check in/check out capabilities to allow efficient return to non-TSP operations.

The limitations of the GPS and radio-based detection systems are:

- Introduces yet another GPS device on-board the transit vehicle.

- GPS system may fail to locate the transit vehicle in some locations due to “urban canyon” effect, which would prevent adequate TSP operations.
- Ease of integration to other on-board vehicle systems is uncertain at this time.
- Limited field implementation in existence and this remains a relatively new technology for communication with traffic signal controllers.

Based on literature reviews, Glendale, California is currently in the process of developing this form of detection. Broward County, Florida currently uses this system for emergency vehicle preemption and has considered its use for TSP. Econolite’s EMTRAC system and 3M’s GPS based systems are two products available for this type of application.

Centralized, AVL-based Systems

This type of detection system is the most reliant on the existing communication infrastructure on the transit vehicle, using the Automatic Vehicle Location (AVL) system. The equipment is comprised of a GPS unit connected to a radio system, which sends information to the Transit Management Center or Traffic Management Center. If sent directly to the traffic management center, the signal system can directly act on the request based on established criteria.

The advantages of an AVL based detection system include:

- No additional hardware on the transit vehicle if a functional AVL system is already in place.
- Data flows may be directly to the traffic or transit management center.
- Ability to transfer information such as vehicle location, speed, and schedule adherence.

The limitations of an AVL based detection system are:

- Latency in receiving requests from buses per their polling rate (unless priority messages are given higher status).
- Requires real-time communication between Traffic Management Center (signal system) and local traffic signal controller (not possible in every jurisdiction).

4.1.1.5 Wi-Fi Wireless Communication Systems

Wi-Fi and Cellular Digital Packet Data (CDPD) wireless communication systems have been deployed in the past in Los Angeles County. However, the CDPD system has been phased out due to expensive leases and limited network availability. The IEEE 802.11 spread spectrum wireless local area network (WLAN), after some initial refinement, has been very successful and is being expanded. This type of detection system is the most advanced of the communication systems described in this report.

WLAN antenna and equipment mounted at intersection (Photo credit: Steve Gota, LACMTA)

The wireless communication system is fairly similar to what is implemented on mobile technology devices. Packets of information are sent via radio waves between the transit vehicle (mobile client) and each intersection (terminal client), both of which are IP addressable. Infrastructure on the bus and in the traffic signal controller cabinet communicates within the available range of the network.

The advantages of a wireless detection system include:

- Effective use of new technology for implementation of NTCIP messages.
- Greater range than many other detection technologies.
- Data flows may be between the vehicle and traffic signal controller, and between the traffic signal controllers using various communications medium available.
- Relatively low hardware cost.

The limitations of a wireless detection system are:

- Initial costs associated with development of specific hardware tailored to meet local traffic signal systems' needs.
- Detection range may be limited by the coverage of the network.
- May be sensitive to line-of-sight restrictions depending on type of antenna used.

4.1.1.6 Transit Vehicle Detection System Summary

As discussed in the previous sections, there are a number of transit vehicle detection modes and systems that could be incorporated in the Transit Signal Priority Market Package. Determining which detection mode and system best fits a local agency's needs is crucial to establishing successful TSP operations.

A literature review produced a recent survey of transit agencies[4] in which a variety of factors were noted in choosing a TSP detection system to best fit the agency's needs. Key survey points are listed as follows:

- "Ability to make use of existing preemption/priority systems and thus partner with emergency, fire and police services." This was typically associated with an optical (light-based) TSP system.
- "Non-fixed detection point based systems, such as optical, to provide detection of transit vehicles before transit vehicle is slowed by intersection queues."
- "Ability to use or upgrade to an AVL compatible TSP system to allow buses priority only when behind schedule, thus minimizing impacts to intersection operations."
- "In hindsight, it would be nice to have a TSP system that can send more data" (in reference to optical).

[4] "Transit Signal Priority (TSP): A Planning and Implementation Handbook". US Department of Transportation, April 25, 2005.

- “Not interested in a centralized system because it would require too much bandwidth, thus selected optical.”
- “Loops were an existing, reliable, cost-effective and proven technology. It also provided consistent operation in the location at which calls for TSP were placed.”

Many agencies across the U.S. are working on developing a tracking system (two-way communications) to determine if the TSP system is functioning properly and to more closely analyze the effectiveness of TSP.

Table 4-1 shows a summary of the various TSP vehicle detection systems and how they compare to a particular agency’s criteria for TSP. The information is based on research and discussions with vendors and transit/traffic agencies where the various detection systems are in place.

Table 4-1: Comparison of TSP Detection Systems

System	Costs			Customize ID & Data Format?	Potential Interface with AVL, schedule?	Tested & Proven Tech?	Central or Local System Typical Applications?	Requires Line of Sight?	Possible Additional Equipment for Implementation		Range	Jurisdictions using TSP detection
	Per Intersection	Per Bus	Operating / Maintenance						Additional Bus Hardware?	Additional Intersection Hardware?		
Smart Loops	$2,000, depends on local contractor	$250	Low (cost of loop)	No	Maybe	Yes	Both	No	Transmitter	Would likely need additional loops at each intersection (check-in/check-out)	Limited only by lead-in cable from loop to controller	Los Angeles; Chicago; Pittsburgh; San Mateo County, CA; Arlington Heights, IL
Optical	$3,500 for card and rack in cabinet $ 6,500 for site setup and installation	$3,000	$2,000 (emitter replacement) Not probable	No	Yes	Yes	Local	Yes	Optical Emitters	Optical detectors, phase selector for controller cabinet	2,500 feet under ideal conditions	Portland, OR; San Francisco; Tacoma; Kennewick, WA; San Jose; Calgary; Houston; Sacramento; Philadelphia; St. Cloud, MN; Salt Lake City; Alameda & Contra Costs Counties (CA)
Wayside or RF based	$35,000 - $40,000 includes mast arm poles for readers	$50 - $600	$50 (tag replacement), $1,000/year	Yes	Yes	Yes	Both	No	None	Roadside reader	Limited only by connection between wayside reader and controller, some readers may be able to detect up to a block away	King County, WA
GPS	$7,500	$5,000	No data available	Yes	Maybe	No	Both	No	GPS/ radio units	Radio receiver, phase selector	2,500 feet with no obstructions	Broward County, FL (emergency vehicle preemption only)
Wi-Fi	$5,000	$5,000 or less	Low	Yes	Yes	Yes	Both	No (may depend on antenna)	Wireless transmitter	Wireless receiver, bridging equipment	1 Mile +/- (Can be increased with additional access points)	Los Angeles County

4.1.2 Traffic Signal Hardware and Software

The traffic signal controller hardware and software standards available today address the issue of TSP, but do not explicitly require specific functionality. The traffic signal controllers that are connected to a centralized communication system will provide the greatest number of opportunities for implementation of transit signal priority. Lack of communication to these traffic signal controllers may require that additional hardware be placed within the traffic signal controller cabinet to provide a link to scheduling or the bus dispatch center that provides feedback from the local intersection.

While communication between a central system and the traffic signal system is not necessary for implementing transit signal priority within all of the scenarios presented, it would enable a centralized implementation and provide enhanced monitoring capabilities that could summarize information from local traffic signal controllers for use in fine-tuning the signal priority system operations during implementation.

The following sections highlight the TSP capabilities of some commonly deployed signal control hardware and software. All modern traffic signal controllers utilize some type of hardware and software to execute control and, where applicable, transit signal priority. The traffic signal control industry has three major hardware standards or "types:" 1) NEMA, 2) Type 170, and 3) the newer Advanced Transportation Controller (ATC) including the Type 2070 standard. The NEMA standard has traditionally had the software bundled with the hardware. The 170 and 2070 standards are primarily hardware standards (except for operating system). The Type 170 controller has typically had limited traffic signal software options. The 2070 has many more software options including software traditionally operated only on NEMA hardware.

The traffic controller cabinet shown above includes a NEMA Econolite ASC/2 controller.

Photo Credit: Peter Koonce

4.1.2.1 Software for NEMA Controllers

Signal controller manufacturers provide all NEMA controllers with a proprietary software package that meets the functionality called for in the NEMA standard. Although not required by the NEMA TS-1 1989 standard, all present NEMA controllers have emergency vehicle preemption capability included in their software. In addition, some manufacturers have begun offering TSP functionality either as a standard feature or through an upgrade in the software. Eagle, for example, offers six priority inputs in the Eagle M40 and M50 controllers. These priority inputs communicate with an internal TSP algorithm, which permits green extension, early green (red truncation), and skipped phases. Eagle has also developed an optional additional algorithm that permits alternative phase splits to be selected by pattern, thereby allowing varying amounts of priority to be given to phases by time of day. Econolite offers an add-on TSP module that provides green extension, early green (red truncation), actuated transit phases, and phase rotation.

4.1.2.2 Software for Type 170 Controllers

A TSP algorithm has been written into the Type 170 W4IKS software (HC11 version). When a priority call is received, this algorithm refers to a set of alternative bus plans, which are predefined by the engineer. Depending on which approach the bus is on and whether the call comes in during green or red, the algorithm chooses an appropriate plan with updated phase force-offs. The City of Portland has implemented TSP at over 300 intersections using the upgraded software.

4.1.2.3 Software for Advanced Transportation Controllers

Type 2070 controllers were developed by Caltrans as a replacement for Type 170 controllers. Type 2070 controllers can be placed in either a NEMA or a Type 170 cabinet. The 2070 is primarily a hardware specification that includes a specific operating system. The upgraded processing power and OS-9 operating system of the Type 2070 allow additional functionality over the NEMA and Type 170 controllers. The availability of TSP algorithms for Type 2070 software will vary by manufacturer. As more software options are developed for the Type 2070 and the demand for TSP capability increases, it is likely that TSP will a commonly available feature for the Type 2070.

> The Type 2070 traffic signal controller was designed through a collaborative effort by vendors and industry leaders. The standard controller was designed by Caltrans to replace the Type 170 controllers.

4.1.3 Communication Technology

Communications on board the transit vehicle between the system components need to comply with SAE J1587 and J1708 standards. This includes the interface between the AVL and the TSP detection hardware on the bus.

Communications between the on-board systems/TSP detection hardware and the local traffic controller have not been defined within any standard beyond what is highlighted within NTCIP 1211 and what is developed in the TCIP initiative. Lacking any clear direction or standard that has been through the approval process, many jurisdictions implementing signal priority throughout the country are not providing any data within the communication between the bus and the signal controllers. Instead they are using a singular system to make the determination regarding whether to request priority (Priority Request Generator) and a separate system to determine whether to serve said request (Priority Request Server). Examples of this would include systems that use an optical-based detection system for presence detection only and are not transmitting any information beyond that to the signal controller.

Many of the detection devices available on the market do not have the capability to transmit large volumes of data with their messages. Some of the devices, like the RF tags and the smart loop, transmit a unique ID number assigned to the bus. The optical devices, as mentioned before, do not transmit any message to the signal controller beyond the limited message identified by the vendor, which is not consistent with any standard developed to date.

Some jurisdictions are making strides on their own and are designing their own specific communication system between the bus and the roadside equipment. They are defining specific data protocols and information to transmit to the signal controller. For example, Los Angeles County is using the IEEE 802.11b standard (consistent with Dedicated Short Range Communication) to communicate between the bus and the local signal controllers.

SAE J1587 describes a Gateway Function for transmitting data from the on-board J1708/J1587 system to another off-board system, such as IEEE 802.3 LAN, via transport protocols. As in the Los Angeles example, a logical extension of this protocol would be to use the Gateway Function to transmit the J1587 on-board bus messages to the local controller via IEEE 802.11, a wireless router and to an IEEE 802.3 LAN within the signal system. These messages could contain information such as on-time performance and ridership, which may allow the signal controller to determine which bus to grant priority when conflicting calls are received simultaneously.

4.1.4 Transit Vehicle AVL System

The integration of an AVL system into transit signal priority systems has the potential to greatly increase the effectiveness of the TSP system through vehicle identification, tracking, and data processing capabilities. These characteristics of an AVL system create opportunities to interface with transit scheduling software to provide conditional TSP service (i.e. priority for conflicting requests, late buses, buses in service, or buses on route) and to improve the route scheduling to take better advantage of signal priority benefits. Data processing is a key requirement in selecting an AVL system. The system should be able to record and transmit signal priority activities to a database or data management system so that TSP operations and effectiveness can be tracked, analyzed, and improved.

AVL and scheduling interfaces could aid in combination with controller software to prioritize multiple TSP requests at an intersection. To maximize the intelligence of an AVL-TSP integrated system, it should also work in as close to real-time as possible with on-board and off-board technologies, such as APCs, vehicle maintenance systems, real-time scheduling software/tracking, database management systems, and geographic information systems (GIS).

Integration of the AVL with the signal priority system requires adherence to the SAE J1587 and SAE J1708 standards. The SAE J1708 standard defines the physical connection on board the bus, and the SAE J1587 standard defines the format of messages and data that are of general value to modules on the data communications link. Included are field descriptions, size, scale, internal data representation, and position within a message, such as:

- Vehicle and Component Information – this includes all information that pertains to the operation of the vehicle and its components
- Routing and Scheduling Information – information related to the planned or actual route of the vehicle, including current vehicle location
- Driver Information – information related to driver activity, including driver identification, logs, performance, and status

Within the J1587 standard, there are a number of Parameter Identifications (PID) necessary to provide the functionality of TSP. Table 4-2 summarizes the required and optional PIDs.

Table 4-2: J1587 Parameter Identification for TSP Use

PID	Name	Use	TSP Requirement
43	Ignition Switch Status	Conditional Priority	Required
74	Maximum Road Speed Limit	Estimated Time of Arrival	Optional
84	Road Speed	Estimated Time of Arrival	Optional
218	State Line Crossing	Conditional Priority	Optional
232	DGPS Differential Correction	Conditional Priority	Required
238	Velocity Vector	Estimated Time of Arrival	Optional
239	Vehicle Position	Conditional Priority	Required
251	Clock	Conditional Priority	Required
379	Door Status	Conditional Priority	Required
381	Vehicle Use Status	Conditional Priority	Required
447	Passenger Counter	Conditional Priority	Required
500	Intersection Preemption Status and Configuration	Conditional Priority	Required
501	Signage Message	No short-term plan identified to use for TSP	Message available for use
502	Fare Collection Unit – Point of Sale	No short-term plan identified to use for TSP	Message available for use
504	Annunciator Voice Message	No short-term plan identified to use for TSP	Message available for use
505	Vehicle Control Head Keyboard Message	No short-term plan identified to use for TSP	Message available for use
506	Vehicle Control Head Display Message	No short-term plan identified to use for TSP	Message available for use
507	Driver Identification	No short-term plan identified to use for TSP	Message available for use

4.1.5 Traffic Management Centers

A TMC is a centralized location for processing data inputs and delivering outputs to the roadway network. Basic processes can occur at a TMC, such as signal system management, decision-making for incident management, and data storage for various intelligent transportation systems (e.g., variable message signs, highway advisory radio, signal timing, transit signal priority). Because of the vast amount of data transmitted to and from a TMC, it requires a large amount of communications infrastructure to operate. The most reliable and fastest (near real-time) operating communications is typically through buried or overhead fiber lines to and from the TMC. In many regions, this may require a new, extensive fiber network that does not currently exist and would be costly to develop.

4.1.6 Transit Management Centers

A TMC is responsible for monitoring and communicating with the transit fleet. This may be done simply through voice communication over radio or may involve data exchange through an AVL system. In order to implement TSP, polling rates for communication between the TMC and the fleet vehicle should be adequate to provide responsive priority decisions. For instance, polling rates for a GPS system are often around 60-120 seconds, which is not fast enough to provide integrated TSP operations.

If transit signal priority is to be integrated into either a Traffic Management Center or a Transit Management Center, one or more of the following requirements should be present:

- Real-time communication between the priority detection system and the applicable center, where priority decisions can be made and relayed back to the local signal controller within 1-2 seconds;
- Real-time scheduling software and other ITS features to help guide whether signal priority should be granted by the center and thus the local controller;
- Real-time communications between the Traffic Management Center and the Transit Management Center, if either center is involved in screening signal priority requests; and
- Database/data storage capabilities to log and analyze transit signal priority operations.

The requirements of the respective centers will depend on the particular scenario that is being implemented.

4.2 TSP Implementation Examples

This section describes in detail two types of TSP system implementations – centralized (LADOT's implementation as the example) and decentralized (Los Angeles County Metropolitan Transportation Authority's and Santa Clara Valley Transit Authority's implementations as examples). These different systems are reviewed and discussed in detail to provide a clear understanding of the implementation requirements for each system. The LADOT and Los Angeles County Metropolitan Transportation Authority (LACMTA) systems are also summarized in Appendix A. The following is a brief summary of the characteristics of the three TSP implementations:

- LADOT TSP system: This system uses loop detectors for vehicle detection and LADOT's own TPS software for centralized TSP control.
- LACMTA TSP system: The centralized TSP system does not work outside of the City of Los Angeles, where LACMTA also provides service. In order to implement TSP at signals that are not in the LADOT's signal control system, LACMTA developed a decentralized TSP system to supplement the centralized TSP. The LACMTA system is designed specifically to be complementary to LADOT's centralized system and is developed based on a WLAN-based vehicle detection system and the existing traffic controllers with minimum software modifications by the controller vendors.

- Santa Clara Valley Transit Authority (VTA) TSP system: Under Caltrans sponsorship, PATH conducted the evaluation of a different decentralized TSP system developed by VTA and Caltrans. The VTA system is designed around the "cost economical" philosophy. Existing loop detectors are used as the means for vehicle detection and identification, in a very similar manner to the LADOT centralized TSP system. However, the VTA system requires less sophisticated traffic controllers (Type 2070 in the LADOT application vs. Type 170E in the VTA application along El Camino Real). While the VTA concept is a variation of LADOT's TSP system, all TSP decisions are shifted to local controllers thus decentralizing system control. The VTA system required a lower budget to implement.

4.2.1 Centralized TSP – Los Angeles Department of Transportation

4.2.1.1 Background

The Metro Rapid Bus Program was initiated in March 1999 by LACMTA as a demonstration program. The initial phase of the Metro Rapid Bus was deployed on June 24, 2000, when the Metro Red Line subway was extended to the San Fernando Valley. The demonstration program aims to offer rail-type frequent and high quality transit services connecting the terminus of the Red Line to major destinations in the outlining areas. Two lines were selected for the demonstration:

- Line 720 Wilshire/Whittier, with very high passenger demand urban corridor connecting through the Los Angeles Central Business District;
- Line 750 Ventura, with high passenger demand suburban corridor serving the Metro Rail Red Line.

Following the successful implementation of the Metro Rapid demonstration program, an expansion program identifying 26 additional corridors was developed. As of December 2005, a total of 15 corridors have been implemented. When completed in 2008, the Metro Rapid Program will operate a network of 450 miles of Metro Rapid service, complementing light and heavy rail transit throughout Los Angeles County.

The TSP system is a key attribute of the Metro Rapid Program. Two types of TSP systems have been implemented in the Rapid Bus Program. The first type uses the TPS software developed by LADOT, which requires a centralized control system and is used in 14 of the 15 corridors mentioned above. The other type is a decentralized system implemented along part of Crenshaw Boulevard. This section describes the hardware, software, communications, and other requirements for the implementation of the centralized TSP system, while the decentralized implementation will be discussed in the next section.

Overview of the Implementation

The TPS software, which was developed and implemented by LADOT for the centralized TSP system, is an independent system from their Automated Traffic Control System (ATCS). Thus in theory, TPS can operate with or without ATCS. The development of TPS consisted of three primary phases:

- Test, design and implement the hardware and software for the detection of the transit buses in order to provide traffic signal priority functions on the first 35 intersections of Ventura Boulevard at the local control level. The buses would be receiving traffic signal priority at all signalized intersections regardless of running time performance.
- Develop a TPM program consisting of a schedule and headway checking routine, the MTA bus schedule database and the two-way communication link between the MTA Operations Center and the LADOT Automated Traffic Surveillance and Control (ATSAC) Center. This "smart" feature would provide traffic signal priority to a particular bus only if the bus is running behind schedule. The system was also extended to cover the remaining intersections on Ventura Boulevard and all of the Wilshire/Whittier Corridor.
- Integrate Phase 1 and Phase 2 into LADOT's ATCS. ATCS program would be able to provide transit priority on a network basis to balance the demands for multiple transit priority requests against those of general traffic. In this implementation, each signalized intersection in the project area is equipped with loop detectors that serve as Automatic Vehicle Identification (AVI) sensors. These sensors embedded in the pavement receive a radio-frequency code from a small transponder installed on the underside of each bus. Buses equipped with unique transponders will be detected when traveling over the loop detectors. These loops are connected to an AVI receiver within the traffic signal controller at each intersection, which then transmits the bus identification number to the TPM computer in the City's ATSAC at City Hall East for tracking and schedule comparison. Once the bus' identification and location are received by the TPM, the computer makes a determination of the need for traffic signal priority. If the bus is early or ahead of the scheduled headway, no traffic signal priority treatment is provided. However, if the bus is late or beyond the scheduled headway, then the downstream traffic signal controller will provide signal priority to help the bus catch up with the scheduled headway.

4.2.1.2 Architecture

A diagram of the TPS system architecture is shown in Figure 4-2.. This TPS architecture is an implementation of NTCIP SCP Scenario 3 (See Chapter 3), where both the priority request generator and the priority request server are located in the Traffic Management Center. The hardware configuration of TPS consists of the following:

- Local controllers upgraded to Type 2070 with LADOT's firmware, which includes transit priority functions
- Piggyback on the existing second-by-second communications backbone

- Unique communication protocol between 2070 controllers and the TPM

The central system configuration consists of the following:

- TPM Server in the central system links with the central control data server through a high speed Ethernet network
- TPM Server determines if priority should be granted by the local controllers
- TPM Server handles the load-balancing algorithm to maintain bus headways

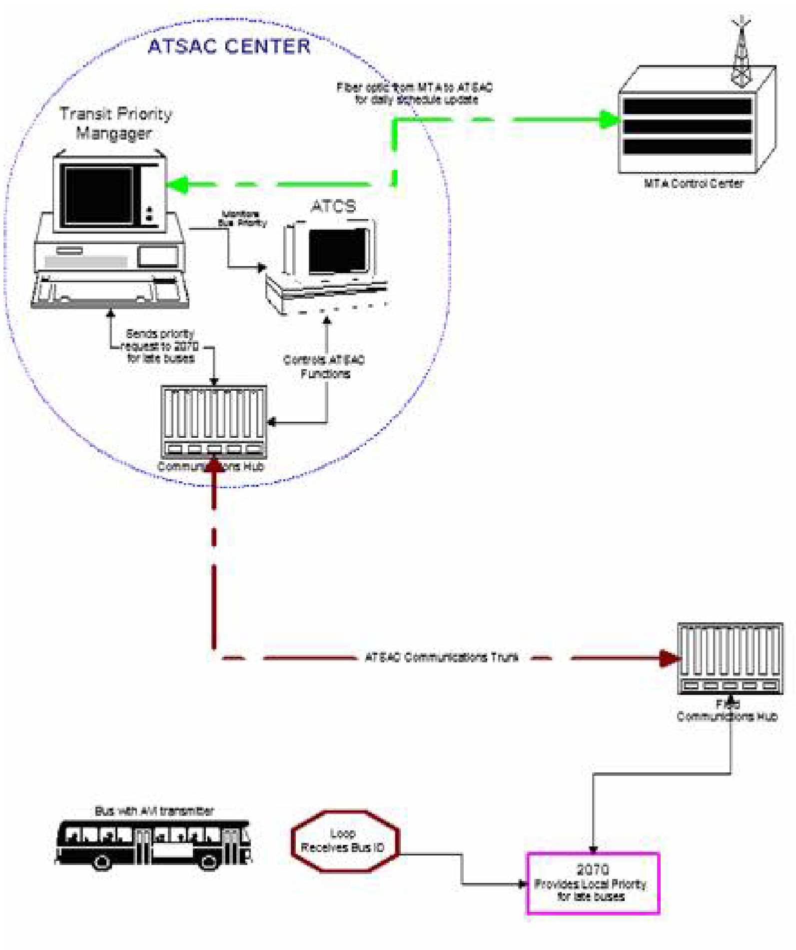


Figure 4-2: TPS Architecture

Sub-Systems

TPS is implemented through several subsystems, which are discussed below.

Vehicle Sub-System

Before the selection of the vehicle sub-system, LADOT conducted a comprehensive field test and evaluation of three different technologies for vehicle detection and identification to permit transit priority at traffic signals. The technologies tested included a radio-frequency antenna-transponder detection system, a loop-transponder detector (LTD) system and an infra-red optical based system. Based on the evaluation criteria of detection reliability, ease of installation and capital and maintenance costs, it was determined that the LTD technology was the most reliable, accurate and cost effective detection scheme for this type of AVI application. The transponders were mounted on the underside of the bus and a permanent power connection was made to the vehicle electrical system. The cost of the transponders was less than $200 per bus (including installation cost). This low cost equipment made it expandable to a large fleet of buses.

Roadside Sub-System

Bus identification loops are installed at intersections. Advance detectors are located just past the upstream bus stop and release detectors are located just prior to the limit line or within the intersection.

The transponder communicates the bus ID with an inductive loop imbedded in the roadway, which is then connected to the traffic signal controller cabinet. The Type 2070 traffic signal controller is an integral part of TPS. It is a first generation Advanced Transportation Controller (ATC) designed by LADOT and Caltrans. The microprocessor-based Model 2070 Controller is designed for field installation in Type 332 and Type 337 cabinets. The City of Los Angeles is using the Type 2070 Controller as a replacement for the Type 170 Controller in many applications including traffic signal control and TPS. For TPS functions, the Model 2070 Controller receives requests for priority treatment from the TPM computer via ATSAC's communications infrastructure and invokes the appropriate functions at the local intersection to provide transit priority. The local Type 2070 controller software was also developed by LADOT staff.

Communications Sub-System

The AVI transponder continuously transmits a unique code. This transponder is crystal controlled and the data are pulse code modulated. There are 19,683 unique codes available. The AVI sensor is coupled to the loop and is factory tuned to 375 kHz. The sensor scans the loop at 250ms intervals. It is designed to receive and respond to any of the transponder's 19,683 pulse-coded signals selected by the user.

The 2070 controller polls these sensors once per second. The data are stored within the 2070 controller until the central TPM computer requests it. The TPM is capable of accessing 64 communication channels at seven intersections per channel for a total of 448 signalized transit intersections. The TPM polls seven 2070 controllers once every second on the same physical communication channel and has the capability to perform auxiliary communications with the 2070 controller for uploading and downloading purposes.

Traffic Control Center Sub-System

Once the Type 2070 traffic signal controller receives a request for priority treatment from the TPS, it implements one of following four types of traffic signal priority actions, depending on the instant in time when the signal controller receives the commands relative to the background cycle:

- Early Green: Priority is granted when a bus is approaching a red signal. The red signal is shortened to provide a green signal sooner than normal.
- Green Extend: Priority is granted when a bus is approaching a green signal that is about to change. The green signal is extended until the bus passes through the intersection.
- Free Hold: Priority is used to hold a signal green until the bus passes through the intersection during non-coordinated (free) operation.
- Phase Call: The signal controller brings up a selected transit phase that may not normally be activated. This option is typically used for queue jumper operation, or a priority left turn phase.

Each intersection is equipped with one or more AVI sensors at the controller cabinet and inductive loops for each direction. Buses equipped with transponders will be detected when traveling over the loop detectors. The sensor unit in the traffic signal controller detects and transmits the bus ID number to the TPM in the ATSAC Center for schedule comparison. If the bus is early or on time, no traffic signal priority treatment is provided. However, if the bus is late or beyond the headway allowance (which is a user-defined parameter, and is usually one minute or more), then the downstream traffic signal controller will provide signal timing priority in order for the bus to make up time. A live data link from the LACMTA center to the ATSAC center was established to obtain the dynamic daily bus assignment for schedule comparison.

Dynamic computer graphic displays, shown in Figure 4-3, were developed to display the transit priority corridors with the status of signalized intersections and loop detectors. Traffic engineers can use the graphic displays to monitor signal operations and the types of transit priority that is currently provided at every intersection. The graphics also show the real-time location of all buses equipped with transponders as they travel along the corridor and through the loop detectors. The bus ID and the arrival time at the loop detectors can also be displayed by clicking on the bus icon. This is a very useful tool for the bus dispatcher to monitor all the buses running within each corridor and to identify late or slow buses. Furthermore, all the bus travel time data are stored in the computer and can be tabulated to track critical bus performance statistics.

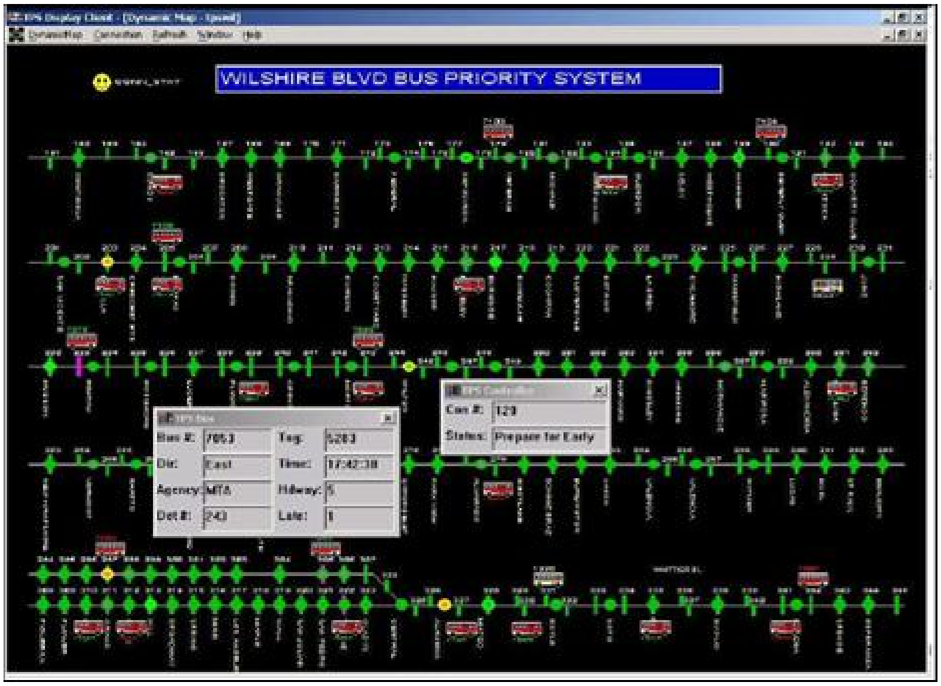


Figure 4-3: TPS Display

Transit Operations Center Sub-System

The TPS project utilizes part of the existing communications infrastructure of LADOT's ATSAC system. TPS operates on a separate computer, yet interfaces closely with the real-time traffic signal system. The large screen projection monitors in the ATSAC Center are used to display the computer graphics for TPS. The extensive closed-circuit television (CCTV) surveillance system that was deployed in the ATSAC system along major traffic corridors, which coincide with many transit corridors, can be selected to view the bus operations and identify incidents affecting transit operations. As a result of the TPS project, LADOT's ATSAC Center has evolved to be a multi-modal transportation management system, which integrates both traffic and transit management functions.

Since LACMTA manages all the regular buses and the Rapid Bus fleet, it was critical to connect LACMTA's Bus Operations Center with the ATSAC system so that bus dispatchers can make maximum utilization of TPS. A fiber optics communications line was established to connect the two centers as part of the project. Several client workstations and large screen monitors were installed in LACMTA's Bus Operations Center (as shown in Figure 4-4) and connected with the ATSAC system via the dedicated fiber. Real-time graphic displays for TPS and live CCTV images are made available to LACMTA's bus dispatchers to monitor and manage the bus fleets along the two project corridors.

Figure 4-4: LACMTA's TPS Workstations

4.2.1.3 Requirements and Cost

This section describes the costs for various components of the LADOT's TPS system.

Bus Detection and Identification

TPS requires advance detectors just past the upstream bus stop and release detectors just prior to limit line or within the intersection. LADOT uses LoopComm Vehicle Transmitters to transmit vehicle ID to the loop detectors. The cost of installing loop detectors is typically $5,000-10,000 per intersection.

Traffic Signal Controller

TPS requires the use of a Type 2070 controller for each controlled intersection. A 2070 controller typically costs $3,000-$4,000.

Hardware and Software for Priority Request Generator and Priority Request Server

The central computer hardware costs $30,000 to $40,000 per system and could control up to 512 intersections.

On the software side, LADOT has partnered with FHWA to make three key software packages (2070 Controller firmware, ATCS, TPS) available for use by other public-sector transportation departments. The packages are offered on a non-exclusive basis through the University of Florida's McTrans Center. The license fee for these packages will include a limited number of technical support hours provided by a technical support agent (TSA) who is experienced in integrating real-time traffic control systems. Support beyond the limited number of hours included in the license fee will require a separate contract between the end-user organization and the TSA. The City of Los Angeles will retain all copyrights and ownership of the software, and will not release source code initially.

The estimated license fees per site are as follows:

- 2070 Controller firmware: $15,000
- ATCS: $30,000
- TPS: $30,000

Communications System

TPS was designed independently from ATCS. It is not necessary to install ATCS as a pre-requisite for TPS (LADOT's TPS is piggybacked on the ATCS communications infrastructure to save capital costs, but it is not a required configuration). Any communications system that allows reliable second-by-second polling from the center to every controller can be configured to run TPS.

Personnel

The personnel cost includes labor costs for control center operations and maintenance. When TPS is operated in conjunction with a central traffic system, no additional traffic engineers are required. The number of traffic engineers needed to operate a traffic control system with TPS depends on the size and complexity of the system. A rule of thumb for human resources used to be that one traffic engineer/technician is required for 50 signalized intersections. Because of the advanced capabilities of ATCS, much of the work of signal timing is automated, so the personnel requirement is considerably reduced. For example, LADOT employs about 20 engineers to control 3,150 signalized intersections. Roughly a third of the engineers are signal timing engineers, a third are traffic engineers, and a third are software, hardware, and communications research and development staff. An outside agency adopting LADOT's system may not need the R&D engineers, but a specialist for system support and upgrades is needed.

In addition, setting up detectors at intersections is a tedious and error-prone process. It requires stringent quality control. A dedicated loop detector crew may be required for the repair and maintenance of loop detectors.

The costs discussed above will be used for identifying various implementation paths in the next section.

4.2.1.4 Implementation

This section describes potential implementation options for an agency that is interested in LADOT's TPS system, followed by a summary of implementation paths, review of the status quo of traffic signal controller, signal control systems, and TSP systems in the United States, and an evaluation of the market for LADOT's TPS system.

The discussion of implementation options are based on the following items: bus detection and identification, traffic signal controller and central system software.

4.2.1.5 Adoption Options for TPS Components

Bus Detection and Identification

LADOT places loop detectors at appropriate locations in the road, and equipped buses with LoopComm transponders to enable bus detector and identification. Although this configuration is shown to function accurately and reliably in LADOT's deployment, other configurations can also be accommodated by the TPS software.

There are many options for implementation of a message from the PRG. For example, if the bus is equipped with AVL and wireless communications technologies, a message simulating one that is generated by a loop detector may be sent to the 2070 controller, although loop detectors are not present. Another example is where an agency would like to use the inductive loop detectors that are currently in place for bus detection. In this scenario, the transit vehicles need to be equipped with transponders at approximately $200 per bus, and the detector cards need to be replaced to accept the bus identification information.

Traffic Signal Controller and Central System Software

As stated earlier, LADOT's TPS software is developed for 2070 controllers in a centralized control system. The software consists of the following two parts: 1) local software (on 2070 controllers) and 2) central software (on system workstations). As previously mentioned, it is not necessary to install ATCS as a pre-requisite for the TPS. In fact, although LADOT piggybacked TPS on ATCS for communications infrastructure capital cost savings, the transit priority mode and the adaptive mode of operations are mutually exclusive at the moment. However, the local TPS software on a 2070 controller currently interacts with the traffic signal by communicating with the Traffic Signal Control Program (TSCP) on the controller through a data module (i.e. socket). The TSCP is written by LADOT staff primarily to accommodate ATCS operations. Therefore, if an agency plans to incorporate TPS with a signal control system other than ATCS, either the TSCP program on the controller should be modified to interact with the signal control system software or the signal control system software should be customized to work with LADOT's TSCP program.

For 2070 controllers that are not loaded with the required firmware, it is usually more cost-effective to replace the firmware with the right model than to modify existing ones. It may take more than a year and as much as $200,000 to modify "foreign" firmware to work with ATCS and TPS software.

By analyzing an agency's signal system inventory, the software used, and the requirements for additional software development, an initial assessment of the infrastructure for the purpose of supporting LADOT programs' deployment can be made.

Summary of Implementation Paths

Based on the above discussion, if a transportation agency wants to adopt LADOT's TPS system, it needs to have a form of bus detection, acquire the necessary central control system and local controller hardware and software, modify its existing communications system, and hire competent personnel for the operations and maintenance of the system. Depending on the local agency's needs, funding, infrastructure and signal management system already in place, the agency may take different options for adopting the TPS. A few implementation paths with different implications on deployment cost and schedule are shown in Table 4-3. There are five columns: the first column is the components in the TPS system, the second column is the current status of that component (for instance, it already exists in required form, it exists in some other form, or it doesn't exist at all), the third column is a list of implementation options if the component is not in the required form already, the fourth column gives the corresponding estimated cost for the option, and the last column contains notes for the option. Please note that the costs listed in the tables are simplified, rough estimates and are not all inclusive. For instance, when a software package is adopted, it shows only the cost of that software package and assumes that all hardware and communication requirements necessary for the software are already met. Furthermore, personnel costs are not included.

4.2.1.6 Performance

The performance of TPS is evaluated with more than 1,000 bus running time data points. According to LADOT, the Metro Rapid Bus achieved 22~28% savings in total travel time as compared to the local transit service. The transit priority system alone contributed to 8~10% of the total travel time savings. Bus delays at signalized intersections were reduced by 34~39%. The impact to cross-street traffic was shown to be minimal, typically averaging about one second of delay per vehicle. In addition, TPS allows MTA to meet other BRT goals by:

- Maintaining even headways between buses;
- Monitoring bus performances;
- Giving bus arrival information to roadside passengers.

Limitations of the Existing System

There are a couple of limitations to the existing TPS system. First, the system is only able to accept transit priority requests on the main street or coordinated phase. Second, after the system provides an initial request for priority, it will not accept another message from the bus until the bus reaches the check out detector, located after the intersection. Thus, there could be lost calls. Although this hasn't been reported as a problem, it could potentially be a problem, especially at intersections with high transit traffic.

Table 4-3: Implementation Options for LADOT's Transit Priority System

Component	Current Status	Implementation Options	Estimated Cost	Notes
Bus Detection and Identification	Exist in required form	N.A.	$0	
	AVL and wireless communications	Modify the message sent to controller so it conforms to the required message format	Software development cost	
	Loop detector without bus identification functionality	Change the detector card in the controller, equip bus with ID magnet	Approximately $150 per intersection, $200 per transit vehicle	
	No bus detection	Install loop detectors and bus transponders	$5,000~$10,000 per intersection	
Signal Controller	2070 Controller with required firmware in a centralized system	N.A.	$0	
	2070 Controller in a centralized system, no LADOT firmware	Implement LADOT's 2070 firmware	$15,000	
		Modify a "foreign" firmware to work with TPS software	Up to $200,000, plus $15,000 for LADOT firmware	
	Other controller types in a centralized system	Upgrade to 2070 controller	$3,000~$4,000 per controller, plus $15,000 for LADOT firmware	
	Other controller types in a decentralized system	Upgrade the system into a centralized system, and upgrade to 2070 controller	Communications system upgrade cost varies; $30,000~$40,000 for computer hardware per 512 intersections; $3,000~$4,000 for each 2070 controller, plus $15,000 for LADOT firmware	
Centralized Traffic Control System	Other signal control system	ATCS	$30,000	
		Customize the control system software to work with LADOT's 2070 firmware	Varies	A major system developer may be willing to customize their control system software to work with LADOT's 2070 firmware. As such, the cost for customization may be shared by several customers of that system developer, not just one agency.
TPS System	No TPS System	Adopt LADOT's TPS	$30,000	This is the software cost. As a pre-requisite, hardware and communications need to meet LADOT's signal control system requirements.

4.2.2 Decentralized TSP – Los Angeles County Metropolitan Transportation Authority

4.2.2.1 Background

Two types of TSP systems have been implemented in the LADOT and LACMTA's Rapid Bus Program. The first type is the centralized TSP system reviewed in the previous section, and the other type is a decentralized system implemented along part of Crenshaw Boulevard (and is being deployed in four other corridors). This section summarizes the hardware, software, communications, and other requirements for the implementation of the decentralized TSP system.

Before February 2004, the Crenshaw Boulevard corridor was served by two bus lines -- Line 210 and Line 310. Both lines provided local and limited-stop service along the corridor between the Hollywood and Redondo Beach areas (Figure 4-5). In February 2004, LACMTA substituted Line 310 with Metro Rapid Line 710. Line 710 offers limited stops with priority service as well as skip-stop service and serves only 45 stops along the 18-mile corridor (average stop spacing is 0.9 miles compared to 0.25 miles for local routes).

TSP is installed at all 33 signalized intersections along the Crenshaw Boulevard corridor. The 33 intersections belong to several jurisdictions, including the cities of Gardena, Hawthorne, Inglewood, Los Angeles, El Segundo, and the County of Los Angeles. The intersections are equipped with four different types of traffic controllers loaded with different control software, as shown in Table 4-4.

4.2.2.2 Operating Principles

Different types of signal controllers/firmware are used in the various jurisdictions, and how exactly priority is granted is a vendor-specific issue. LACMTA and LADOT only specify the bus-to-intersection message format and how the bus request for priority should be accepted by the controller.

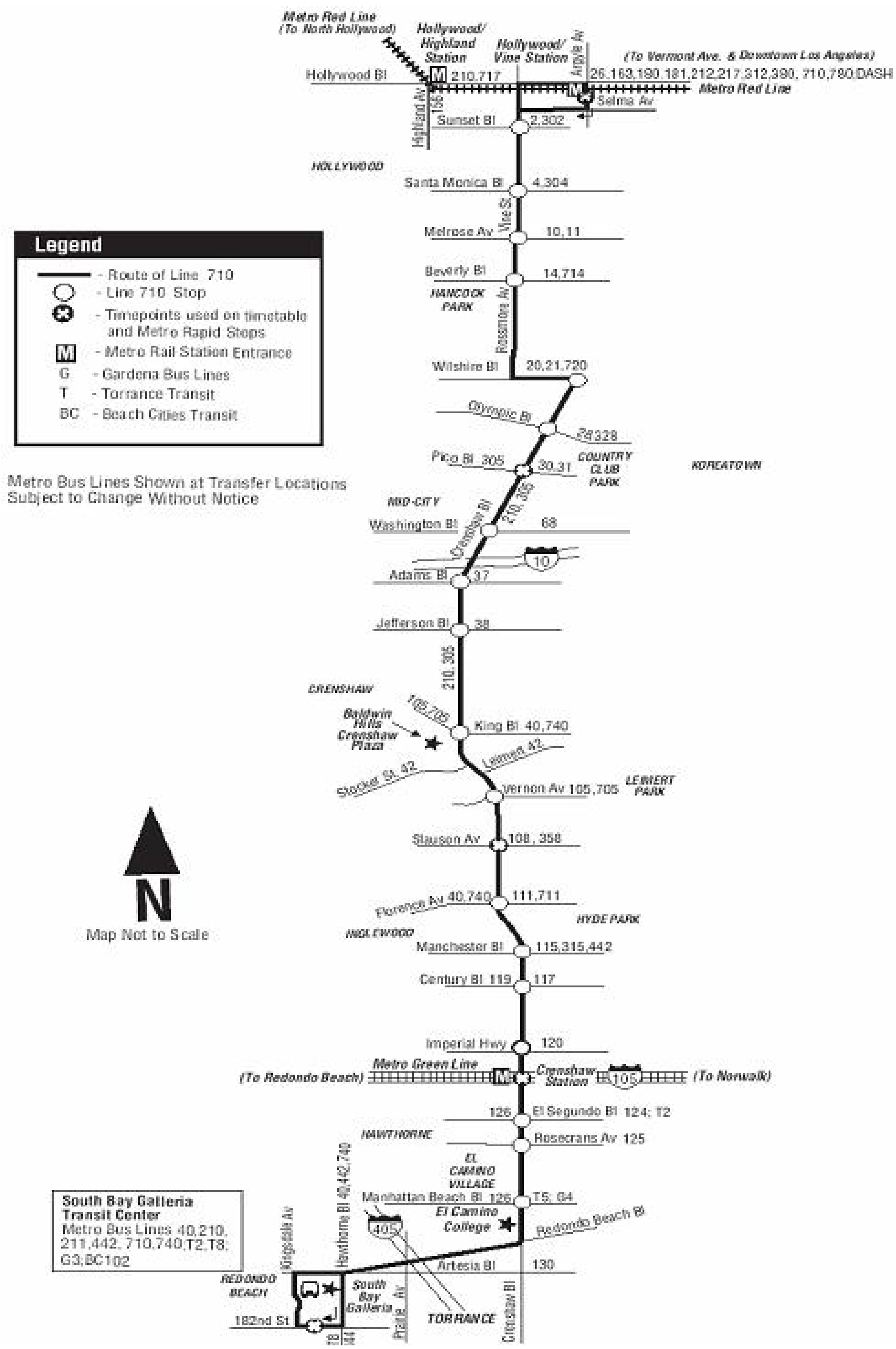


Figure 4-5: Crenshaw Boulevard Corridor Line 710 (Source: http://www.metro.net/)

Table 4-4: Traffic Signal Controllers along Crenshaw Boulevard Corridor

Jurisdiction	Number of Intersections	Traffic Controller	Firmware
City of Los Angeles	**10**	**2070**	**LADOT**
City of Inglewood	**14**	**170E**	**BiTran233**
County of Los Angeles	**7**	**2070, 170E**	**LADOT, LACO-4**
City of El Segundo	**2**	**2070**	**LADOT**

4.2.2.3 Architecture

LACMTA's TSP system along Crenshaw Boulevard is an example of a Scenario 4 decentralized architecture implementation. As shown in Figure 4-6, in this system, the PRG is located on the bus while the PRS is at the traffic controller cabinet.

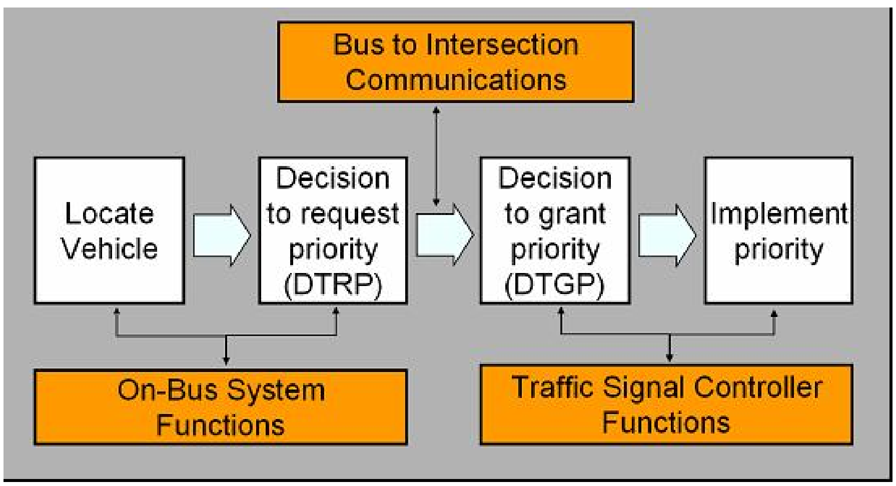


Figure 4-6: Decentralized LACMTA TSP Process

The overall communications architecture for the TSP system is presented in Figure 4-7. In the hierarchical system, an IEEE 802.11b WLAN is the backbone communication between buses and intersections.

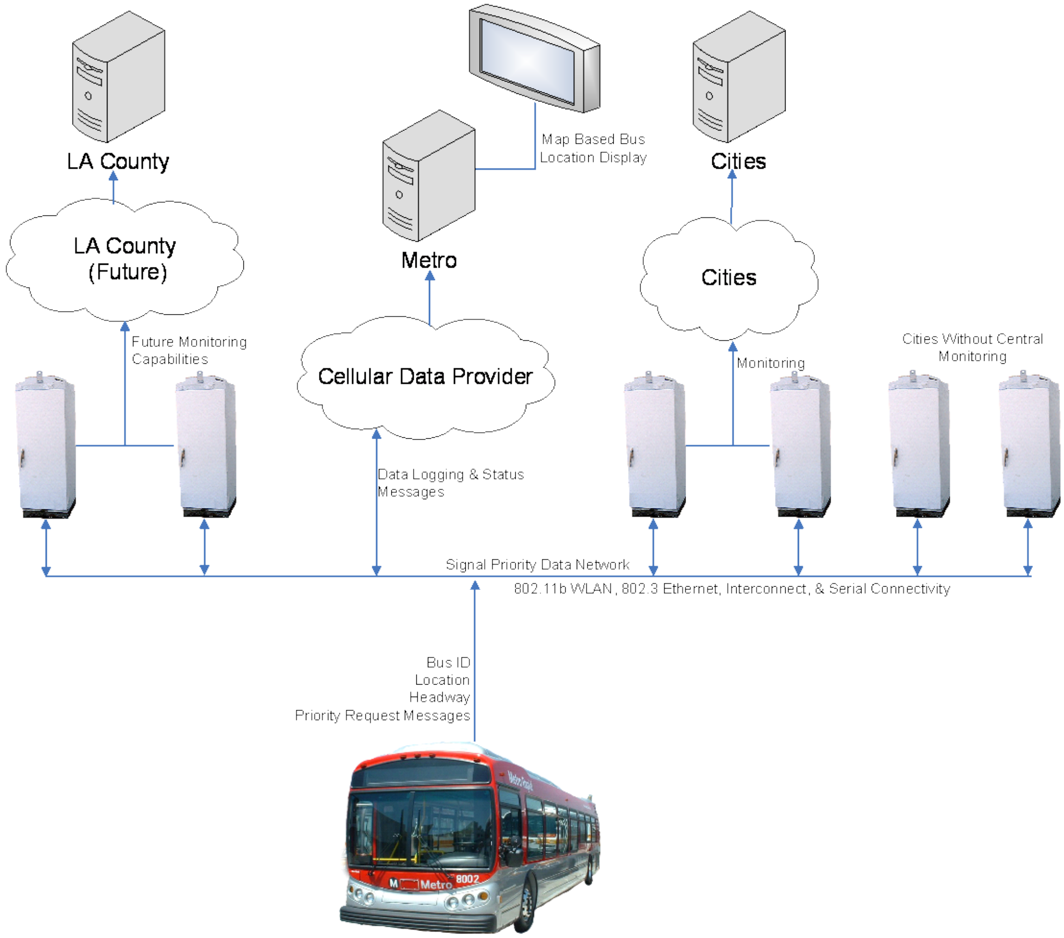


Figure 4-7: Signal Priority Communications Architecture

4.2.2.4 System Components

Each function is realized through various components of the TSP system. The components include the on-bus system, bus-to-intersection communications, and the traffic signal control system.

On-Bus System

The LACMTA TSP project is based on the concept of a "smart bus unit" -- an AVL system that is capable of identifying the current location of the bus and the necessary logic to determine if and when to request priority from upcoming traffic signals using an on-board IEEE 802.11b-based spread spectrum radio communication system. The core of the on-bus "smart bus unit" is a UNIX based PC, as shown in Figure 4-8. These units are installed on transit vehicles, as shown in Figure 4-9. The antennas for GPS and on-board IEEE 802.11b-based spread spectrum radio communication are typically installed on the front top of the vehicle, as shown in Figure 4-10.

Figure 4-8: On-Bus "Smart Bus Unit"

Figure 4-9: Typical On-Bus Unit Installation

Figure 4-10: Typical GPS and Wireless Communications Antenna Installation

Priority Request Generator

The PRG is installed in the on-bus system. For the Crenshaw Boulevard corridor, TSP requests will be generated unconditionally at all signalized intersections when supported by the intersection control firmware. The on-bus system transmits the bus route number, direction, and scheduled headway information to the intersection controller.

The time when the on-bus system initiates a TSP request is based on the predicted time-to-arrival (TTA) at the next intersection. The on-bus system predicts the TTA through a two-step process. The first step takes place when the bus departs from the yard, and the on-bus system software automatically determines the bus run assignment by comparing its position against operating schedule data, which has been downloaded into the on-bus system. The second step involves the on-bus software continuously checking for the upcoming intersection along its assigned bus route. The on-bus system constantly checks the current bus position and smoothed speed acquired by the GPS, and predicts the TTA to the upcoming intersection.

Communication Hardware

WLAN systems provide a means for mobile network clients (i.e., TSP-equipped buses) to utilize the 2.4 GHz radio spectrum to communicate with intersection traffic signal controllers equipped with wireless antennas, receivers, and terminal servers. A WLAN using the IEEE 802.11 specification is typically made up of devices known as access points (APs) which function to bridge wired and unwired networks and a client device that provides wireless network service to a device, such as a signal controller. IEEE 802.11-based WLAN systems were never intended to be utilized for long range communications. However, with the correct antenna technologies, a single AP can provide network service to a radius of up to one mile and, in some circumstances, even longer distances. Extended coverage ranges can be achieved by deploying additional APs, allowing the individual coverage areas to overlap slightly as depicted in Figure 4-11Figure 4-11.

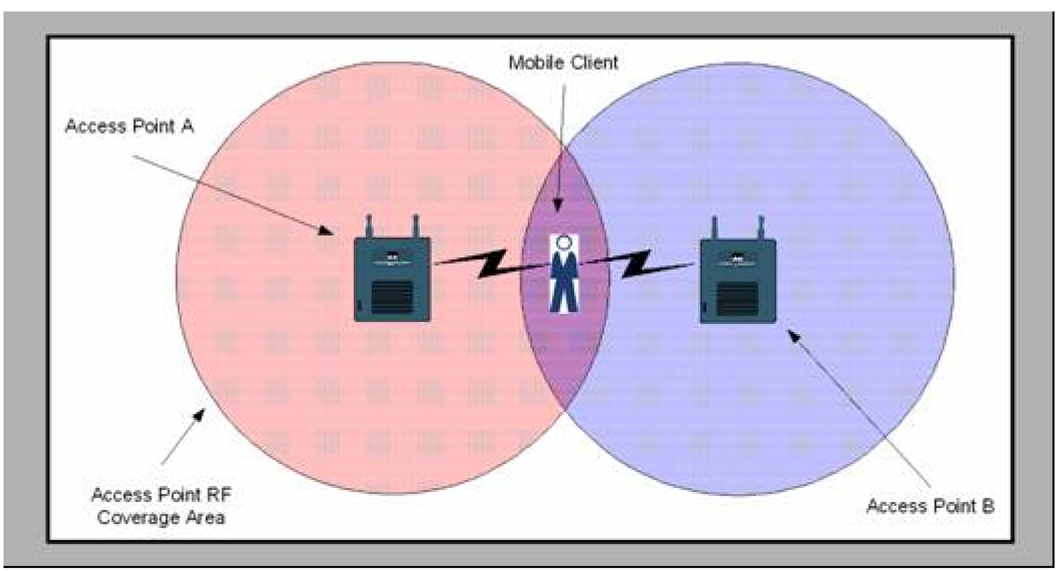


Figure 4-11: WLAN Technology and Design

Installing a series of APs with overlapping coverage areas offers ubiquitous Radio Frequency (RF) coverage to create continuous network access for the corridor. The fundamental design issue related to the deployment of the corridor-wide wireless network is the interconnection of the APs in order to allow for seamless roaming of the TSP-equipped buses.

In order to deploy a WLAN in a corridor, two types of intersection hardware are used: 1) bridging/AP equipment at roughly every fourth signalized intersection, and 2) client equipment required at other signalized intersections.

A network bridge is a specialized WLAN device that provides point-to-point communications as shown in Figure 4-12. It can be used to create the necessary common network infrastructure between APs that permits seamless communication in decentralized traffic signal systems because such systems normally have no signal interconnections or other wired communications to serve as the backbone of the various APs.

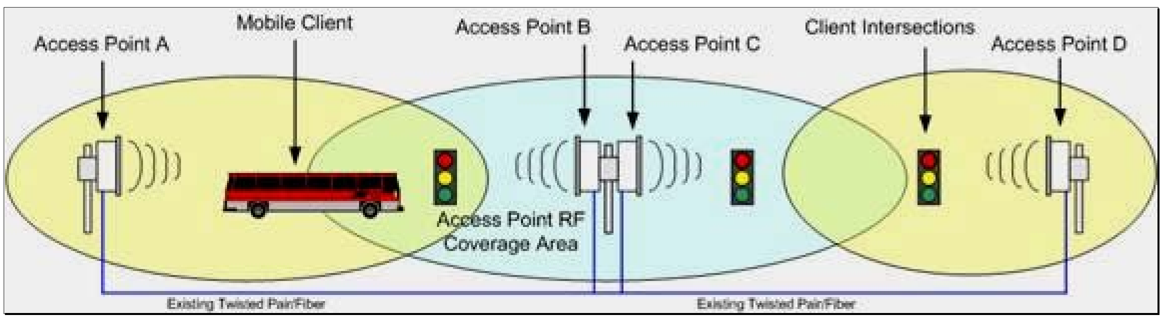


Figure 4-12: Typical WLAN Bridging Configurations

The point-to-point links between signalized intersections support communications among the client intersections and TSP-equipped buses. Such a system requires much less hardware to be deployed and also minimizes network management and maintenance requirements.

To implement the proposed design, an intersection serving as a bridge/AP intersection on a corridor requires the installation of a Cisco 1300 series bridge pair on the signal pole or mast arm at the maximum possible height (as shown in Figure 4-13Figure 4-13). Installation requires the mounting of the bridge with its integrated antenna on the signal pole or mast arm and running coaxial cable from the bridge enclosure to additional equipment housed in the controller cabinet.

Figure 4-13: Typical WLAN Bridge/AP Equipment Installation

In a Type 332 traffic controller cabinet, a custom-fabricated aluminum panel is installed on the back side of the cabinet, hinged so that signal technicians can easily move the WLAN hardware out of the way when needed for signal maintenance. The additional equipment mounted on the panel includes a terminal server and power supply equipment for the pole-mounted hardware as shown in Figure 4-14.

Figure 4-14: Front and Rear Views of Bridge/AP Intersection Panel

At each client intersection, a terminal server that converts the IP-based wireless communications data packets to serial data for traffic signal controllers is installed in the traffic controller cabinet as shown in Figure 4-15. Additionally, small antennas are installed on top of the traffic controller cabinets and connected to the terminal server, as shown in Figure 4-16.

Figure 4-15: Typical WLAN Client Intersection Cabinet Installation

Figure 4-16: Typical WLAN Client Antenna Installation

Any system operating within unlicensed spectrum has interference issues. Site surveys were performed prior to the deployment in order to evaluate the current RF propagation characteristics of the corridor. The system monitoring functions are built in, allowing for operations and maintenance monitoring. LAMTA and its contractors have been monitoring and addressing any new sources of interference in the area. To date, the results show that there have been no interference problems along the Crenshaw Boulevard corridor.

Communications Protocol

For each priority request, three messages are transmitted using the on-board IEEE 802.11b radio. Two of the messages are check-in messages. The other message is for check-out purposes. With the current configuration for Crenshaw Boulevard Line 710, the check-in message is sent to the intersection using the WLAN when the bus is estimated to be 20 seconds away from the intersection. An update message is sent to the intersection five seconds later for redundancy and to account for any traffic conditions as the bus approaches the intersection. Finally, as the bus enters the intersection, a check-out message is sent to allow the intersection controller to cancel any additional priority extension to reduce the impact to cross traffic.

The communications protocol between TSP-equipped buses and the intersection server is User Datagram Protocol (UDP). The broadcasting protocol is simple and involves no error checking. Consequently, the receiving end is not aware of lost messages, commonly referred to as “packets”. To address the potential packet loss in this system, the protocol requires the resending of the message five seconds after the initial message. LACMTA field tests show that a very small percentage of initial request messages are not received by intersections, and nearly 100% of messages were received after the second messages were transmitted, indicating that UDP is adequately stable for the LACMTA TSP system.

Bus-to-Intersection Message

The priority request message set is initially defined based on an NTCIP SMTP format; however, after several revisions, the current version of the message is not NTCIP compatible. The message set includes the bus identifier, bus direction, bus route, predicted time-to-arrival, and scheduled headway. The detailed message format is shown in Table 4-5.

Table 4-5: Bus-to-Intersection Message Format

Field	Data	Description
1	Hex 0x7e	Start Flag
2		Address Packet, Variable length (1-3 bytes)
3	Hex 0x03	Control (send data no response)
4	Hex 0xc3	Initial Protocol Identifier (IPI)
5	Hex 0x8N	Command (0x80 STMP + 0x05 Bus Status with N Data bytes; N=5 for Pilot Project Protocol, N=8 for Metro Rapid Protocol)
6	Hex 0x0R	Protocol Revision (R=1 Pilot Project Protocol; R=2 Metro Rapid Protocol)
7		Data, Bus Identifier (Two bytes) MSB, LSB
8		Data, Bus Status Bits: 1 N/B Bus direction 2 S/B Bus direction 3 E/B Bus direction 4 W/B Bus direction 5 Position update 6 Check-out 7 Check-in 8 Priority Request
9		Data, Bus Estimated Time of Arrival (ETA)
10		Data, DTGP Action Bits 1 Hold the Green Phase (Bus arrives during green) 2 Early Green Return (Bus arrives when not green) 3 Special Operation (Future; queue jump or skip phase) 4 Demand Override 5 Manual Override 6 Table Override 7 Priority Override 8 Preempt Override This field will not be sent by the bus to the intersection when checking in and is reserved for recording the action taken by the intersection controller in response to the request for priority. The DTGP field will be added to the bus check in message by the traffic signal control equipment for the message going back to the BSP On-bus Processor or BSP Network Monitor. NOTE: The DTGP Action bits may be specific to the controller firmware.
11*		Scheduled Headway (One byte) - Metro Rapid Protocol Only
12*		Bus Route (Two Bytes) – Metro Rapid Protocol Only
13		CRC (Two bytes) MSB, LSB
14	Hex 0x7e	End Flag

Traffic Controller Software Modification

Four types of signal control software are used in the different jurisdictions along the Crenshaw Boulevard corridor. The LACMTA TSP system interfaces with all these different traffic controllers and software.

For the signal controllers to receive the transit vehicle check-in and check-out messages, all controllers were modified to receive the transit priority request and message. Additional functions have been added in the LADOT's 2070 controller software and LACMTA's LACO-4 controller software to track actual bus arrival intervals at the controller level. LACMTA paid the signal controller equipment manufacturers for the modifications of the controller firmware as part of the project. The intellectual property of the modifications is maintained by the manufacturers and LADOT.

Priority Request Server

The information transmitted from the on-bus system to the signal controller includes the scheduled headway, bus line number and direction. The additional functions on 2070 and LACO-4 controller software enables the controller to track the actual headways by bus route and by direction, and thus makes it possible for the controller to grant conditional priority based on how far the bus is behind the scheduled headway. Currently, the Metro Rapid buses running along Crenshaw Blvd. receive conditional priority at 2070 and LACO-4 controlled intersections.

Once the decision to grant priority is made, the controller will then implement priority, following the general rule that allows for a green time extension or early green return of up to 10% of the cycle time, and not more often than every other cycle. The priority execution follows the following process:

- Record the predicted arrival time of the bus from the on-bus system
- Convert direction data into phase information
- Calculate vehicle arrival time in relation to the current cycle
- Decide the type of transit priority: "Green Extension," "Early Green," "Phase Call," "Free Hold," and "No Priority"
- Modify signal timing according to the following priority type:
    - Green Extension: Hold the priority phase green to either the maximum green time or until a check-out message is received.
    - Early Green: Shorten side street timing and provide the maximum early green time for the priority phase.
    - Phase Call: Place a phase call for the left-turn phase to help buses make the turns.
    - Free Hold: When the signal is running free (without coordinated cycle), the controller will hold the priority phase green for a specified amount of time even when there is a conflicting call on the cross streets.
    - No Priority: If the predicted bus arrival time falls within the normal green time of the priority phase, there would not be a need for priority treatment.

- Record actions -- the type of priority implemented and the actual time extended are recorded in the controllers and can be retrieved for performance evaluation

4.2.2.5 Cost

On-Bus System Cost

The on-bus system is provided by a third party vendor. The cost is $9,500 per unit plus approximately $500 per bus for installation. The total $10 K per bus does not include the one-time costs for prototype development, testing, installation plans, and the costs for installation coordination and management, acceptance testing, and documentation.

Communications System Cost

The cost for the communications system, not including the communications equipment on the buses, averages between $3,000 and $5,000 per intersection on a typical corridor, depending on the intersection spacing and other corridor characteristics. Operational costs are not known but are believed to be minimal based on LACMTA's experience over two years of operation on the Crenshaw Boulevard corridor.

Traffic Controller Firmware Modification Cost

The software modifications cost between $40,000 and $80,000 per controller type. This cost is a one-time cost. Where EPROM upgrades are required, the site license cost is $500~$700 per intersection. However, the modification is proprietary and only LACMTA has an arrangement for obtaining a license at this cost at this time. Transit agencies who are interested in deploying these TSP features need to negotiate with the vendors for software license/changes.

4.2.2.6 Requirements

The decentralized LACMTA TSP implementation does not rely on a complicated centralized control system. Instead of having intelligence at the central traffic control system make decisions about requesting or granting priority, the LACMTA system distributes these functions to the on-bus systems and traffic signal controllers. Most controllers already have the capability of implementing priority with green extension and early green features. The fact that LACMTA already paid for the upgrade of the firmware for four types of controllers makes it easier for other agencies to procure these from perspective vendors/agencies with regular licensing fees.

For those cities that do not have a centralized traffic signal control system, the WLAN system offers an opportunity to implement TSP without requiring a comprehensive communications infrastructure. The trade-off of this system is the higher cost for the on-bus systems, which is approximately $10,000 per bus compared to approximately $200 per bus for the loop-transponder technology used in LADOT's TSP system. If the local agencies have a large transit fleet, the total cost for the on-bus systems can be relatively expensive. Should the on-vehicle system be migrated to be a function of the AVL system, the on-vehicle equipment cost will be significantly lower.

Table 4-6 shows the implementation options and associated costs for the different components in the LACMTA distributed system.

Table 4-6: Implementation Options for LACMTA TSP

Component	Current Status	Implementation Options	Estimated Cost	Notes
Bus Detection and Identification	Buses already equipped with Orbital or Siemens system with TSP functionality	Implement WLAN communication transmitter on the vehicles that interface with the AVL system	Unknown	LACMTA is planning to incorporate the TSP function into Orbital's AVL/ACS but no schedule or budget has been established for doing so. LACMTA is also talking with Long Beach Transit and the City of Long Beach to incorporate the TSP function into the Siemens advanced transit management system.
	Other	Install the on-bus system Implement the WLAN communication system	$10,000 per bus $3,000~$5,000 per intersection	
Signal Controller and Signal Controller Software	170E w/ LACO-4 170E w/ Bi-Tran 233 2070 w/ LADOT 2070 firmware Econolite ASC/2	N/A	Unknown	Note that the software modification is proprietary and thus there is currently no means for technology transfer. However, it could be possible for other agencies to procure the software with regular licensing fees.
	Other types of controller/controller firmware	Controller software needs to be modified to provide priority capability	Based on LACMTA's experience, the development cost is between $40,000 and $80,000 per controller type. The implementation cost will be approximately $500~$700 per intersection.	Note that the development cost is likely to be a one time cost and LACMTA already paid for four controller types.
Signal Control System	Decentralized system	Collect messages from traffic controller cabinets	N/A	A communications system between the field and the center (TMC) needs to be established if a central monitoring function is needed.
	Centralized system		N/A	

4.2.3 Decentralized TSP -- Santa Clara Valley Transit Authority

4.2.3.1 Background

VTA and Caltrans have deployed BRT along a major arterial corridor, El Camino Real, in the Bay Area, where Line 22 and its express line, Rapid 522, are operated. VTA TSP system was designed and installed by Caltrans Traffic Operations, Caltrans District 4 and VTA. The philosophy behind the design is to implement a cost-effective TSP based on existing discrete or decentralized traffic control systems with minimum modifications.

VTA Line 22[5]

Line 22 is the backbone of the VTA bus network. Line 22 provides service along the east-west length of the Santa Clara Valley between the transit center at Eastridge Shopping Center in San Jose and the Caltrain station in Menlo Park. The corridor is twenty-seven miles long, as illustrated in Figure 4-17. VTA Line 22 buses run every 10 minutes during weekdays, primarily along King Road, Santa Clara Street, Alameda and El Camino Real (SR 82). Line 22 serves the cities of San Jose, Santa Clara, Sunnyvale, Mountain View, Los Altos, Palo Alto, and Menlo Park. It is VTA's most heavily used line, carrying over 23,000 riders daily and representing 16% of VTA's total bus ridership. The line operates near capacity, with many buses at standing room only.

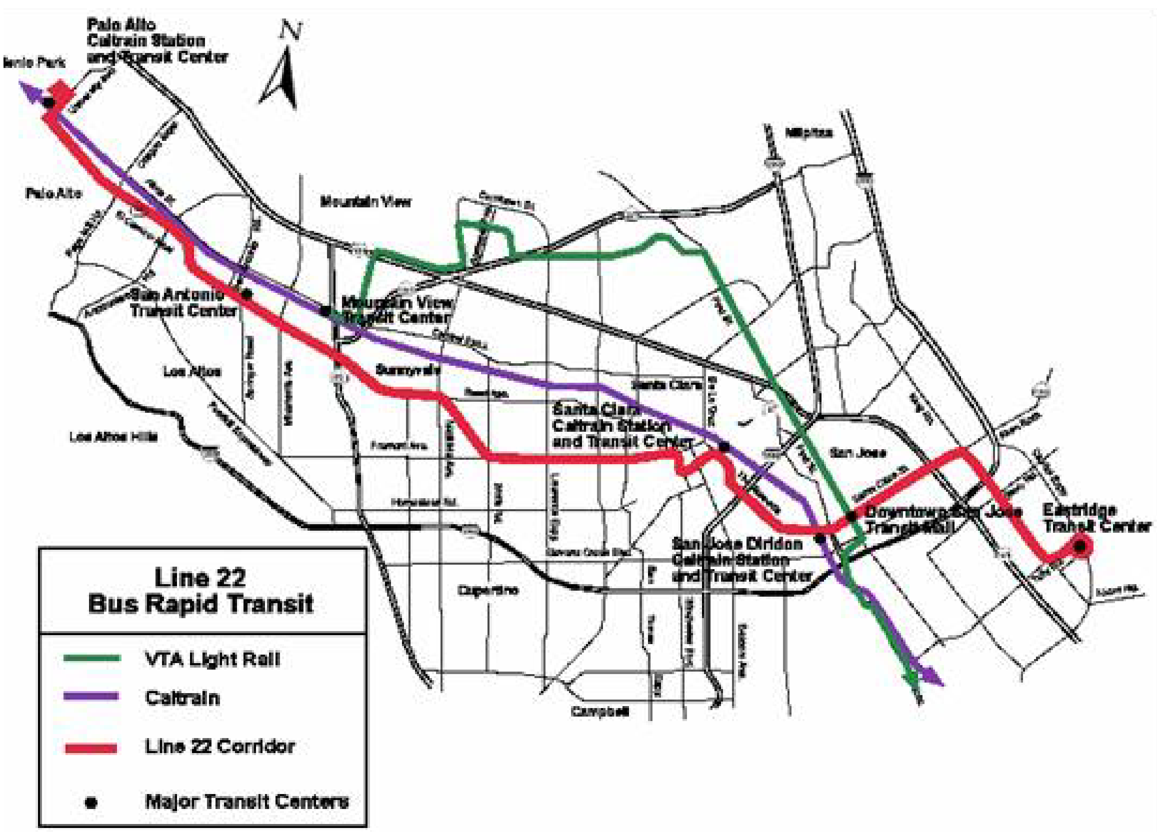


Figure 4-17: VTA Line 22 Corridor (Source: VTA)

[5] http://www.vta.org/projects/line22brt.html

VTA Rapid 522

Line 22 is supplemented by Line 300, a limited stop express service along generally the same corridor. Lines 22/300 connect with regional rail services as well as 55 VTA bus lines. A major connection occurs in downtown San Jose, where Line 22 intersects the north-south Guadalupe Light Rail Line. VTA's vision for Line 22 is that it operates as a "BRT Corridor." To achieve this vision, VTA has implemented VTA's Rapid 522 to replace Limited Stop Line 300 and supplement Line 22, providing faster, more frequent, and more direct service between Eastridge in San Jose and the Palo Alto Transit Center. The service frequency for Rapid 522 is 15 minutes on weekdays. The service combines state-of-the-art technology and service enhancements, including:

- Queue jump lanes at congested locations
- Advanced communication system
- Signal prioritization for buses to reduce delay
- Improved passenger facilities at stops
- High capacity, easy-access, and cleaner buses
- More frequent and direct service

Implementation Site

As part of the Line 522 BRT deployment (Phase I), TSP was implemented, initially at 28 intersections over a distance of 5.8 miles along El Camino Real between Churchill Avenue in the north and Grant Road/Highway 237 in the south. Queue jumpers at two intersections, southbound El Camino Real at Page Mill Road and Arastradero Road, respectively, have been constructed. Figure 4-18 illustrates the TSP implementation site.

Along the El Camino Real corridor, Caltrans operates almost all of the signals. The Caltrans signals use Model 170E controllers running Caltrans C-8 local traffic signal controller software.

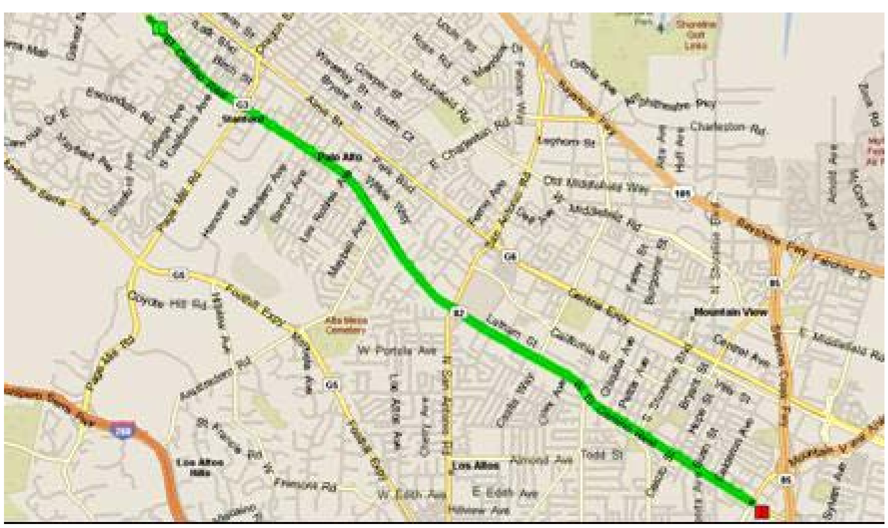


Figure 4-18: VTA Line 522 TSP Implementation Site

Operating Principles

TSP operating principles for the corridor have been developed based on Caltrans' draft TSP operating guidelines. The operating principles are described in Table 4-7.

Table 4-7: VTA Rapid 522 TSP Operating Principles

1. **Priority for Late Buses** – The initial design is to allow buses that are late by a predetermined amount of time to be granted signal priority. Currently, the interaction between the bus's on-board AVL system and transponder is not established, and therefore this function is not yet included in the current system.
2. Priority Call Frequency – The local controller has a user settable parameter for specifying how frequently requests for priority will be granted. This parameter works by monitoring a counter that is incremented each time the local cycle timer zero point is surpassed after a priority call. The default for this parameter is to grant a priority call every other traffic signal cycle.
3. Priority During Transition – Requests for priority while the local controller is in transition will be recognized, but not granted. For example, after a priority call is processed, the controller will have to transition to get back into step. During this time, priority requests received will be recognized, but not granted. However, a transition signal cycle that passes the local cycle timer zero point will increment the priority frequency counter.
4. Priority After Preemption or Power Failure – A railroad or emergency vehicle preemption or a "long" power failure is typically followed by a transition period. The operating principles for priority during transitions govern during these instances.
5. Priority Call on Coordinated Signal Phases – A priority call can either extend the coordinated phases (typically phases 2 and 6 in Caltrans controllers) or bring the coordinated phase up early. Green extension is achieved by holding the coordinated phase green for a user-set amount of time or until a checkout call is received. Early green is achieved by shortening remaining non-coordinated phase green intervals by a settable percentage as feasible.
6. Phase Skipping – Skipping of phases or phase intervals is not permitted.
7. Manual Operation – Manual operation by a bus operator is not possible.
8. Review of Operations – Review of TSP operations is to take place every 60 days by Caltrans and VTA.

4.2.3.2 Architecture

A high-level flow chart for TSP implementation along the Line 522 corridor is shown in Figure 4-19Figure 4-19. The flow chart generally describes the process from the single call for priority placed by an advance detector loop to checkout or termination of the call for priority. This TSP system is an implementation example of logical architecture Scenario 1, where the priority request is generated by the bus and served by the traffic controller.

The data logging of time stamps of priority requests and executions takes place in a "super" master computer residing with the field master controller. The "super" master and its accessories are housed in a separate 332 traffic cabinet. The system is essentially a series of local area networks and information is transmitted to Caltrans' central office in Oakland via a frame relay technique. Figure 4-20 shows the complete system configuration, including the communication links between the field devices and Caltrans' central office in Oakland and VTA's offices in San Jose. Caltrans engineers developed additional software to facilitate the transmission of information from the "super" master to Caltrans' central office.

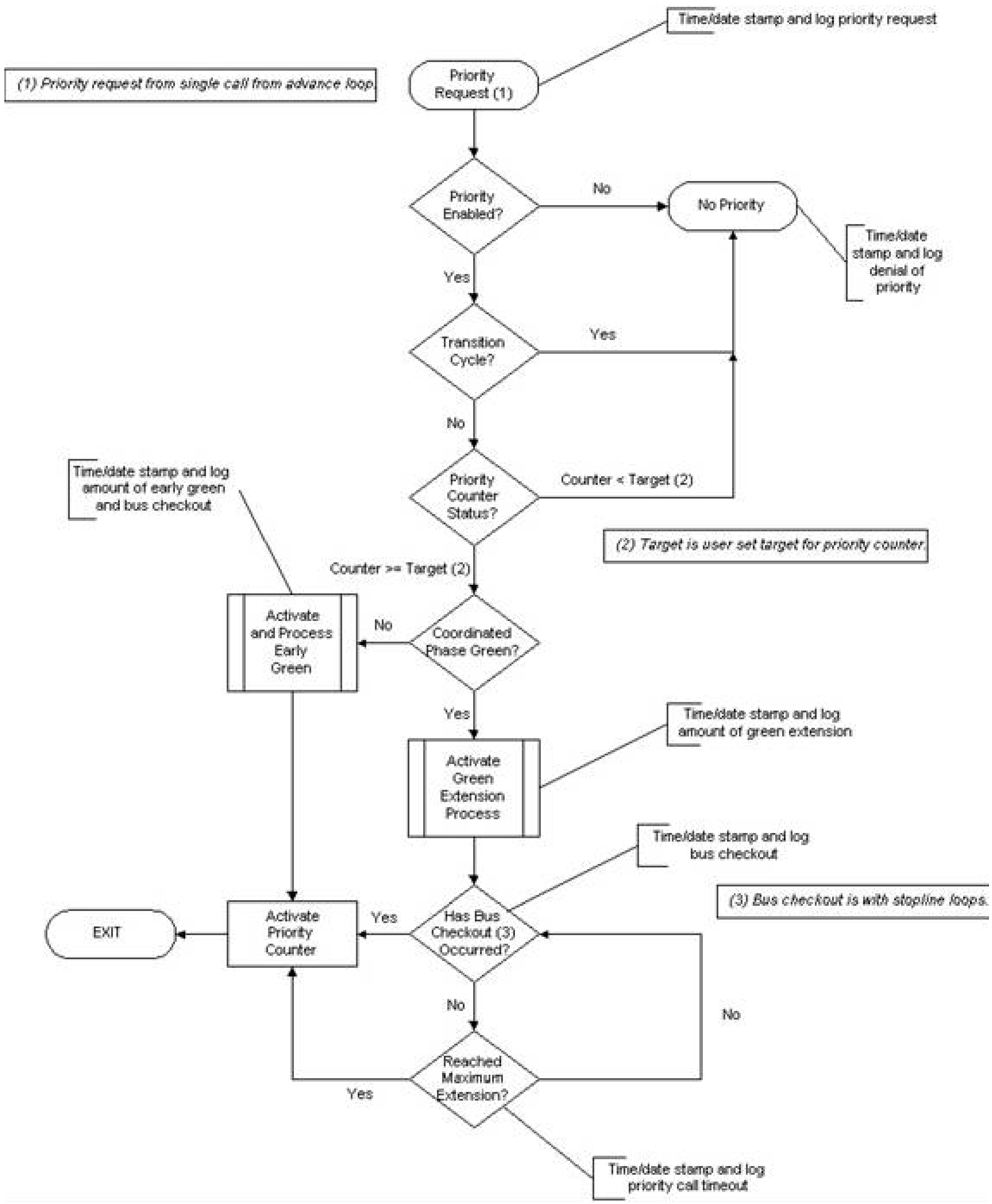


Figure 4-19: VTA TSP Operations Flow Chart

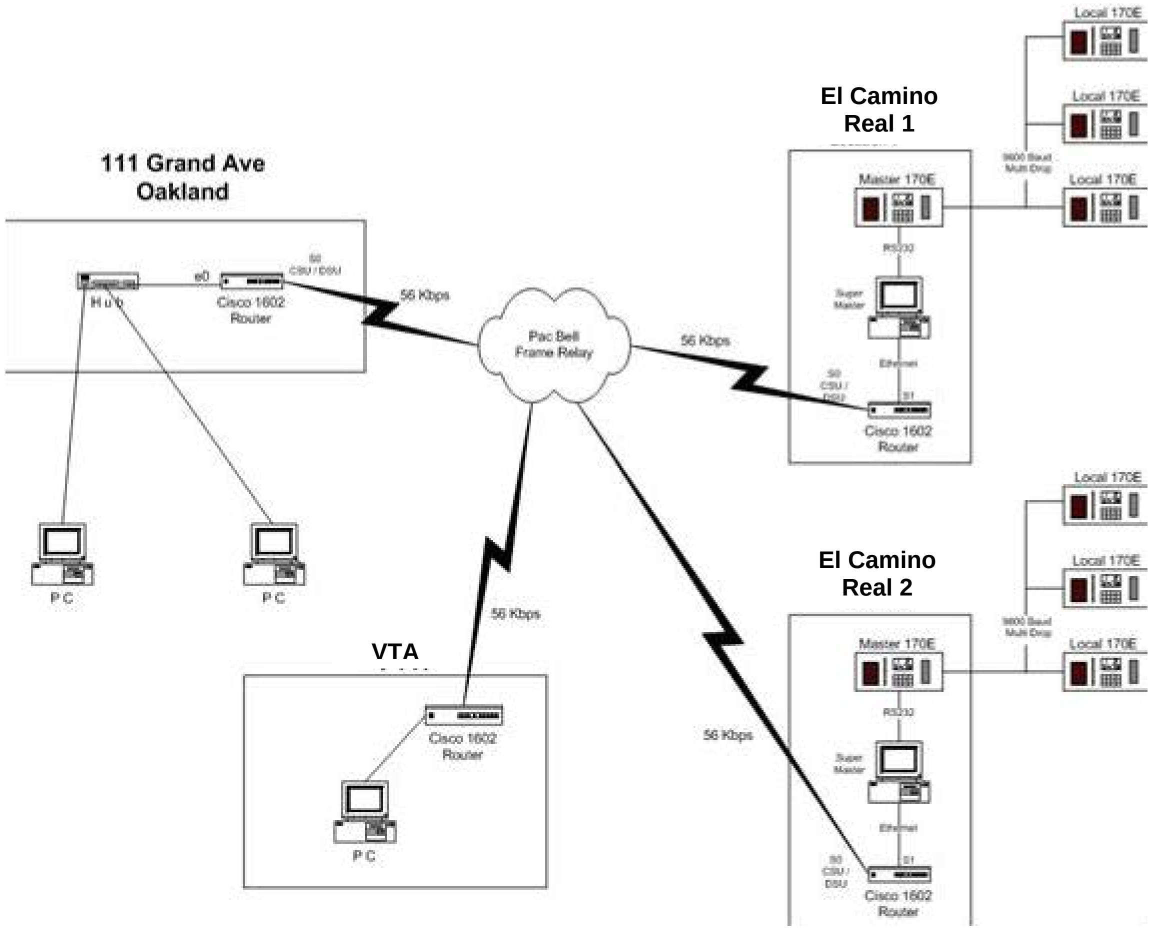


Figure 4-20: VTA TSP System Infrastructure

4.2.3.3 System Components

Transit Vehicle Detection

The TSP system developed by Caltrans and VTA utilizes loop-transponder technology to detect the presence of buses. A transponder mounted under a bus, as shown in Figure 4-21, is designed to continuously transmit a unique code that identifies the bus. Buses equipped with transponders transmit the bus ID when traveling over loop detectors. At each intersection, the existing advance and presence detection loops are connected with a dual channel digital loop detector that can decode the code transmitted by the bus. Currently, the controller deems the reception of bus ID as a TSP request and processes the priority based on the operation principles. Note that VTA is planning to incorporate the schedule adherence feature by interfacing the transponder with the on-board AVL system. While the bus is on schedule, the power to the transponder will be switched off and thus no priority would be granted. When the bus falls behind schedule by some predetermined amount of time, the AVL system will switch on power to the transponder. However, note that this feature is not implemented at this time.

In order to reduce overall system cost, existing detector loops, both advance and presence, are employed for the initial VTA TSP implementation, as shown in Figure 4-22. The existing advance loops, about 190 feet upstream of the stop bar, are closer than ideal, but far enough to still allow a bus to be detected in most cases where a traffic queue exists. The priority request call is cancelled via "checkout" at an existing presence detector. Ideally, the "checkout" detector should be beyond the stop bar, but use of the existing presence loops is able to provide an acceptable level of service.

Figure 4-21: Inductive Loop Transponder Mounted on Underside of a Bus

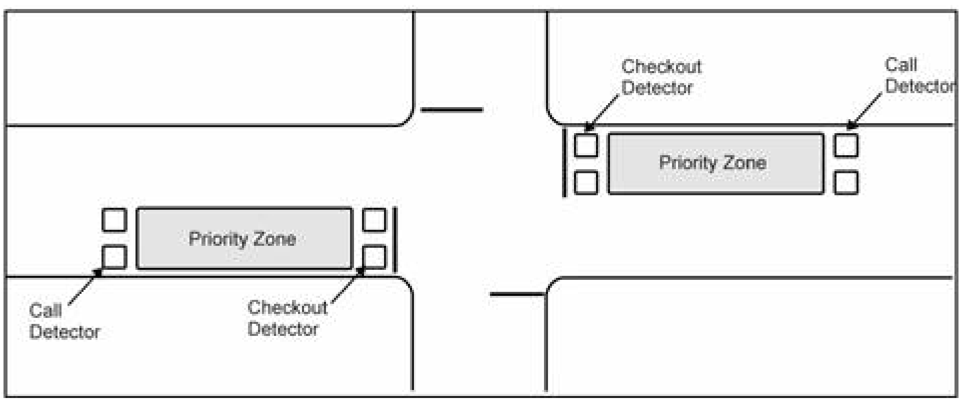


Figure 4-22: Bus Detection Zones

Traffic Signal Controller and Software Enhancement for TSP

The signal control system in place is a closed-loop distributed control system with Model 170E controllers operating Caltrans C-8 local traffic signal controller software. The signal controller software was modified to allow window stretching to respond to a priority request call. A bus priority request call received during the red phase would shorten the green time allocated to movements that conflict with the bus movement and make the green phase along the bus movement direction active earlier than normal (typically called Early Green). A call during the green phase for a bus movement would extend the green phase along the bus movement direction (typically called Green Extension). This TSP strategy is only used with far side and mid-block stops. The enhancements for TSP have been incorporated by updating the C-8 software to facilitate TSP operations. When a bus is detected, the TSP control logic is as follows:

- If the green of the main phase is on, the green is extended until either the maximum allowable green extension time (10 seconds) is reached or the bus passes the intersection.
- If the green is off, force-off points for all minor phases are moved forward by speeding up the local cycle timer until the bus passes the intersection. The acceleration rate is a user settable parameter. For example, an acceleration rate of 20 percent results in 1.2 seconds of clock time incrementing in the controller during a one-second period.

The recovery time required between servicing of subsequent priority calls is defined by the allowable priority call frequency, a user settable parameter in the local controller software. The initial TSP system was implemented for coordinated signals. Additional enhancements were made later to allow the TSP function to be implemented at discrete signals and at signals without presence loops (for check-out purpose).

Communication System

Typically, in a decentralized TSP system, the communication between the field equipment and a central location (e.g., TMC) is not necessary. For the VTA Rapid 522 implementation, a communication link was established between the field masters and Caltrans' central office in Oakland for data logging, and the archived data are later used for system evaluation. Time and date stamps and other information are recorded in real time. To establish the link, a "super" master computer, communication modems and accessories are housed in a separate 332 cabinet and reside with the field master controller. Frame relay over phone lines (with service provided by SBC) is used as the communication link between the "super" master and the central office.

4.2.3.4 Cost

Since the VTA TSP system used the current advance and presence loops as bus detectors and existing 170E traffic controllers with only minor software modifications, the total cost of the system is low. The cost breakdown of the system is described in the following sections.

Equipment Cost

At each field master location, the following instrumentation is needed for the optional communication link between the field devices and Caltrans' central office:

- Industrial Quality PC $3,000
- Network Card for the PC $100
- Four-port Ethernet Switch $100
- Frame Relay Modem $300
- External 9600 Baud Modem $600
- Cooling Fan Matrix $500
- Uninterruptible Power Supply $200
- Type 332 Cabinet $5,000
- **Total** $9,800

At the intersections, each dual channel digital loop detector with AVI capability costs $600. The vehicle transmitter costs $150.

Software Development Cost

The software development cost for enhancing the 170E controller and "super" master was $2,500.

4.2.3.5 Requirements

The prerequisites for deployment of the VTA TSP concept are: 1) existing or newly installed loop detectors, 2) bus transponders, and 3) traffic controllers that can be configured to accept TSP requests. The option of interfacing with the AVL system to provide conditional priority to late buses is desirable but not necessary for implementation. The communication system with the central traffic control system is for data logging purposes and is not absolutely necessary for the TSP system to work properly. The data logging feature can be performed at the local traffic controller level, allowing data to be downloaded manually.

Table 4-8 shows some implementation options, listing various components needed for the VTA TSP system. Note that since this is a decentralized system, the priority granting decisions are all made at local controllers, thus necessary modifications are also mostly made at the local level.

Table 4-8: Implementation Options for Deployment of VTA TSP System

Component	Current Status	Implementation Options	Estimated Cost	Notes
Bus Detection and Identification	Existing advance and presence loop	The detector card in the controller needs to be upgraded for AVI functionality Buses need to be equipped with transmitter	Approximately $600 per intersection, $150 per transit vehicle	
	No detection	Install loop detectors and bus transponders	$5,000~$10,000 per intersection	
	Other more advanced detection technology (e.g. AVL and wireless communication)	Modify the controller software to accept the check-in message	Software development cost, ~$2500 total cost	
Signal Controller and Controller Software	170E w/ Caltrans C-8	Software enhancement needs to be loaded	No licensing fee for Caltrans after the software enhancement has been approved, only labor cost	
	Other types of controller/software	Controller software needs to be enhanced to incorporate priority capability	~$2,500 total cost	The controller does not need to be changed. Controller software needs to be enhanced. $2,500 is estimated cost for the development for TSP features for Caltrans C-8 software. Costs for other controllers may vary.
Signal Control System	Decentralized system	N/A	See “Notes”	A communication link between the field and the center (TMC) is needed if central monitoring function is required. Based on VTA experience, the cost is about $9,700 at each field master.
	Centralized system	N/A	N/A	

4.2.4 Adaptive TSP

4.2.4.1 Background

TSP deployments have demonstrated positive effects on reducing bus intersection delays and improving service schedule adherence. However, concerns have been frequently raised that priority operations may interrupt the normal operation of signal control and thus increase delays to other traffic, particularly those served by the non-prioritized phases (often minor phases, including cross-street and main street left-turns).

Under many circumstances, the above concerns are in fact legitimate. The state-of-the-practice for active TSP systems often adopts ad-hoc or heuristic TSP control logics, which are not adjustable in a real-time manner. For example, early green operation may truncate all of the preceding phases to minimum greens for traffic and pedestrians. Such kind of operations would cause severe delay to the minor-phase traffic, and residual queues could last for several cycles. In order to address the concerns, priorities should be granted only when they are warranted and in a way that minimizes impacts to other traffic. Undoubtedly those priority strategies should be adaptive to real-time traffic, pedestrian conditions and bus arrivals.

On the other hand, active TSP systems normally adopt selective vehicle detection means that sense the presence of an approaching bus only at a fixed location, and thus have difficulty obtaining the exact bus arrival time to an intersection, if the detection means are placed far from the intersection. To ensure efficient priority treatments, the detection location has to be in close proximity to the intersection. Consequently, the resulting "short notice" only gives the signal control system limited lead time to change signal settings to provide priority, which may inevitably cause noticeable delay to the non-prioritized traffic. In contrast, continuous detection means, such as GPS and AVL, are able to monitor a bus's movement. With the improved capability of predicting bus arrivals to intersections, TSP systems should operate more efficiently.

Many transit agencies have installed a GPS-based AVL system on their fleet. For example, by 2005 there was more than 2,500 equipped buses in the San Francisco Bay Area. If the TSP system can be built upon the GPS/AVL system, it would have a continuous bus detection means. More importantly, the deployment will be cost-effective, because it allows buses instrumented with a GPS/AVL system to become TSP capable without requiring any additional equipment on the buses.

In light of the above considerations, California PATH, in collaboration with Caltrans Headquarters and District 4 has been developing an adaptive TSP (ATSP) concept. The main features of the ATSP concept include:

- Providing priority to transit vehicles if warranted while trying to make a tradeoff between bus delay savings and the impacts on the rest of the traffic
- Making real time decisions adaptive to the movements of transit vehicles, traffic conditions and signal status
- Utilizing GPS/AVL to continuously monitor bus locations and predict bus arrival times to intersections

- Building upon closed-loop signal control systems with 170E controllers, which may have potential for wide-scale implementation

System Implementation

The adaptive TSP implementation is along a segment of El Camino Real, north of the VTA site. The segment is located within San Mateo County starting in the north at Crystal Spring Avenue and ending in the south at 31st Avenue. It is mostly a homogenous section with four lanes in each direction (outer lane for parking) and consists of 14 signalized intersections. The total length is approximately 2.3 miles (3.7 kilometers). The minimum space between two signalized intersections is 295 feet (90 meters) and the maximum space is 2000 feet (610 meters). This is one of the most congested areas along the El Camino Real corridor with a range of intersection types, including three-way and four-way intersections, and a range of cross street traffic.

The signal control system is a closed-loop distributed control system with Model 170E controllers operating Caltrans C-8 local traffic signal controller software. The original C-8 was upgraded to provide early green and green extension treatments for transit vehicles. A software switching technique was implemented in the enhanced C-8 program to have the local controller either disable the TSP function, or provide TSP treatments in SamTrans mode (adaptive) or VTA mode. The switch can be remotely set by the super master or upon the requests by the priority requester physically located on a PATH computer.

SamTrans Route 390 is one of the county's major bus lines serving the corridor, running from the Daly City BART Station to the Palo Alto Caltrain Station. There are nine bus stops in the southbound direction and eight of them are located on the near side of the signalized intersections. In the northbound direction, there are 10 bus stops of which five are near side stops. Figure 4-23Figure 4-23 illustrates Route 390, the TSP corridor and individual TSP intersections. Table 4-9 lists the cabinet number and cross street for each of the 14 signalized intersections. All of the intersections are located in the City of San Mateo.

Note that this corridor is not currently a BRT or TSP corridor. However, the corridor has served as a test bed for the ATSP system. In addition to the ATSP implementation, the signal control software installed along the corridor is able to provide TSP treatments in the same mode as the VTA system. It is also feasible to update the software appropriately to mimic operations of other TSP systems, such that real comparisons of efficiency and impacts of different TSP systems can be made from field operations.

Figure 4-23: Intersection Selection along SamTrans Route 390, San Mateo County

Table 4-9: SamTrans TSP Intersections in San Mateo

Cabinet #	Cross Street
E35I5	Crystal Spring Rd
E35I4	2nd Ave
E35I3	3rd Ave
E35I2	4th Ave
E35I1	5th Ave
E35H0	9th Ave
E35H9	12th Ave
E35H8	Barneson Ave
E35H7	17th Ave
E35H6	20th Ave
E35H5	25th Ave
E35H4	27th Ave
E35BA	28th Ave
E35H3	31st Ave

4.2.4.2 Architecture

The system architecture of the ATSP system is illustrated by Figure 4-24.

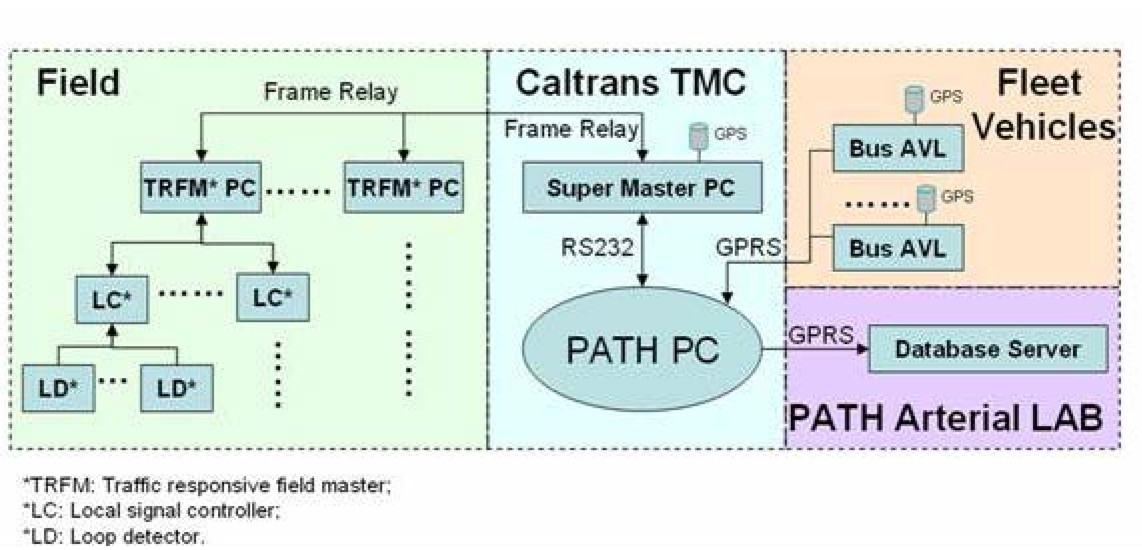


Figure 4-24: System Architecture of the ATSP System

Portable GPS installed on buses transmit second-by-second bus location information via GPRS to a TSP master computer, physically located in Caltrans District 4. A bus arrival time predictor (ATP) hosted in the master computer uses the historical and real-time GPS information to predict bus arrival times to intersections. The master computer also hosts a real-time database, a PRG and a PRS. The computer is connected with the super master of the signal control system by a direct serial port connection, allowing traffic data and signal status to be received by the real-time database. The PRG uses bus arrival prediction, signal status and pedestrian presence information to determine TSP strategies. The PRG sends a priority request message to the PRS whenever a bus needs it and a check-out request after the vehicle passed the signalized intersection. Upon receiving priority requests from multiple buses, the PRS will prioritize all the different priority requests based on the requested priority treatments, requested phase, and desired service time, and then generate a service request and send the service request to 170E signal controllers for execution.

As its name suggests, it is the TSP Master Computer that initiates TSP requests, determines TSP strategies, prioritizes TSP requests, and sends service requests to signal controllers for execution.

4.2.4.3 System Components

The hardware components of the ATSP system have been discussed in the previous section. The other critical aspect of the system is its software components, which are discussed below.

A PRG is the key to determine what kind of TSP strategies. An advanced PRG should be able to adaptively and optimally select either early green or green extension to implement and determine the corresponding signal timing strategies for the TSP operations. The objective is to make a tradeoff between bus intersection delays and other traffic delays. The level of the tradeoff can be adjusted via a weighting factor and should be determined through negotiations among the stakeholders on how much preference the transit operation should be given. The framework of the PRG is depicted by Figure 4-25Figure 4-25.

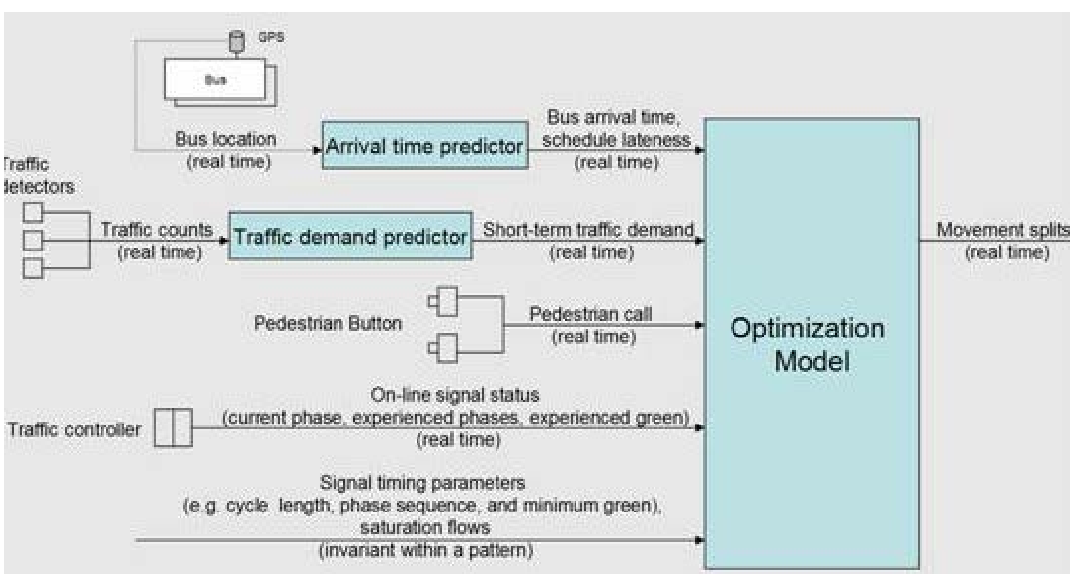


Figure 4-25: PRG Framework

The PRG consists of three important modules: 1) a bus arrival predictor, 2) a traffic demand predictor, and 3) signal timing optimization models. These three components are described below.

Bus Arrival Time Predictor

The developed ATP uses real-time bus location and bus wheel speed information, together with historical AVL data to predict bus arrival times to the next traffic lights. The predictor consists of two models: 1) a historical model that uses linear regression to predict the arrival time solely based on historical data, and 2) an adaptive model that uses recursive regression and adaptively adjusts its filter gain from the real-time AVL data. The final prediction generated by the predictor is a weighted average of the predictions from these two models. The weighting is also adaptively adjusted according to error variances obtained from the historical and adaptive models.

To further improve the predictor's performance, a Kalman filter based bus state observer has been included to smooth the measurement noise and to track bus movements. A kinematics model is applied to model the bus' acceleration and deceleration movement along moving sections and it leads to an updated version of the historical model. A case study evaluates the effectiveness of the updated adaptive model and shows that the prediction error falls into a +/- 5 seconds range when the bus is 300 meters or 24 seconds from the intersection.

Traffic Demand Predictor

To consider the impacts of TSP operations on buses and other traffic, future traffic demand is prerequisite, at least for several TSP impacted cycles. A traffic demand predictor is developed for this purpose. Based on loop detector data from pervious cycles, the adaptive recursive least-square method is applied to predict cycle-based traffic flow.

Signal Timing Optimization Model

The core of the PRG is the optimization models. The inputs to the optimization models are predicted bus arrival times, predicted traffic demand, pedestrian presence information, and signal status. The outputs from the optimization models are TSP strategies (either early green or green extension), and the corresponding pattern of force-off points. Two models are developed -- one for early green and the other for green extension. With justifiable assumptions, analytical closed-form expressions of bus delay and traffic delay for each movement with either early green or green extension have been derived and incorporated into the objective functions of the models. A set of constraints have been developed to guarantee the under-saturation condition, to follow the ring-barrier structure of actuated controllers and to ensure safety. The models are essentially quadratic programming problems and are thus easy to solve.

The Implementation Site

The ATSP system was implemented and tested along the El Camino Real corridor in San Mateo, CA. Figure 4-26 shows the testing site along the corridor. Within this site, 20th Avenue is the only intersection which is not TSP capable because its controller firmware is different from those at other intersections.

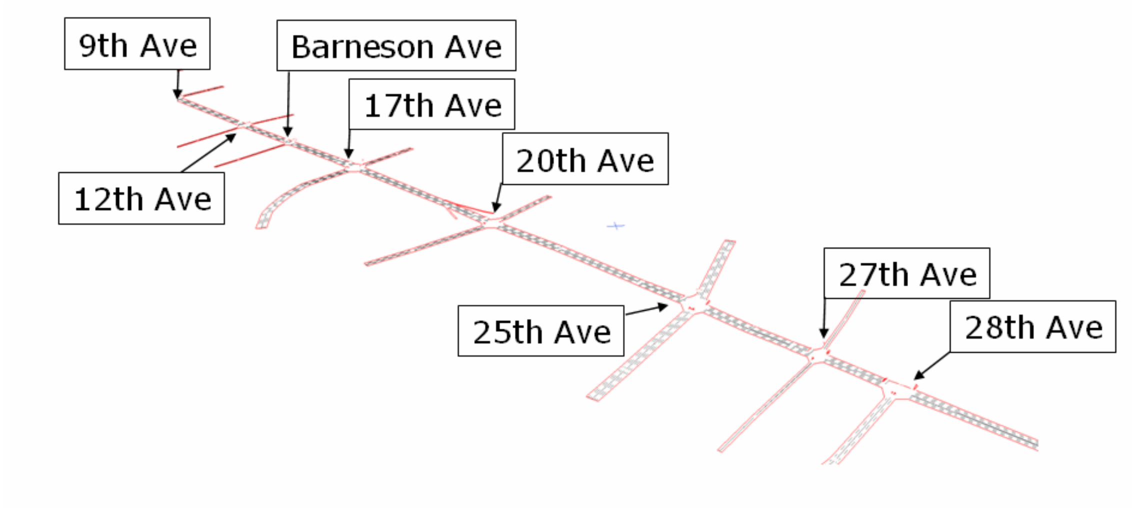


Figure 4-26: Test Site

Hardware Upgrade

A laptop PC was set up in the control cabinet at 9th Avenue. The traffic response field master (TRFM) control software, which was loaded in the 170E signal controller, was installed on the laptop PC. Rather than performing the normal signal coordination functions and ATSP request functions, the laptop PC performs system monitoring, logging and trouble shooting functions.

Software Upgrade

As shown in Figure 4-27, there are fifteen modules in the ATSP software architecture. Twelve of these modules were developed and upgraded by PATH.

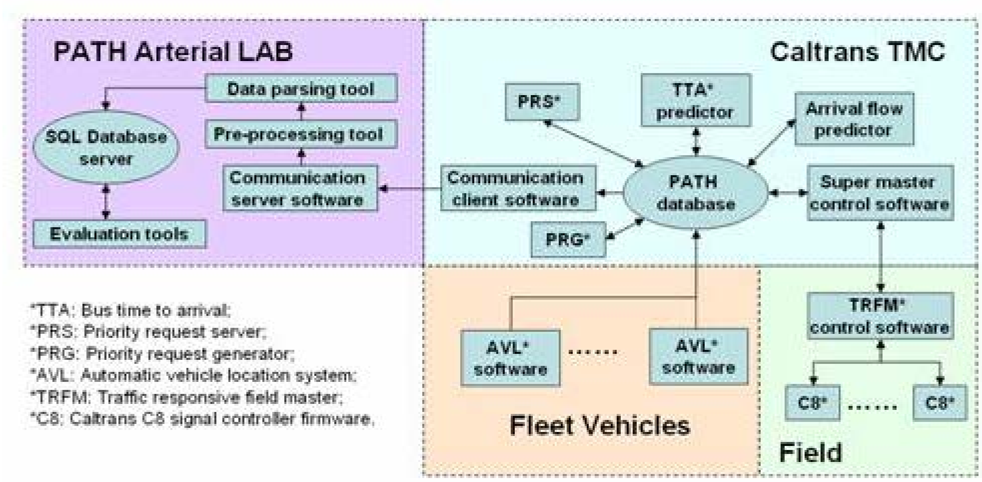


Figure 4-27: ATSP System Software Architecture

Some modules were updated because of operating system upgrades or aforementioned hardware upgrades. The operating system on the PATH computer, which is located at the control center in Caltrans District 4, was upgraded from QNX-4 to QNX-6. Accordingly, the PATH database and other software which are hosted by the PATH computer were upgraded to QNX-6 version too. The AVL communications software and communications client and server program, at Caltrans TMC and PATH arterial lab respectively, were updated because of the communications hardware upgrade.

A major challenge in developing data processing tools using file-based programs is to synchronize numerous data files with various file formats, including transit vehicle movement files, traffic signal status files, loop detector output files, and other software component output files. Thus, the PATH team chose MySQL, the most popular open source database software, to serve the data management purpose. After the database was set up properly in MySQL, three software modules, including data pre-processing, data parsing, and evaluation modules, were developed using the MySQL application programming interface (API) based on those previously developed file-based programs.

Three other modules, including the super master control software, the TRFM control software and Caltrans C8 signal controller firmware, were developed by Caltrans engineers. The super master control software, which acts as the ATSP system monitor and data exchanger between the PATH computer and the TRFM, has not been changed since the previous development project. The other two software applications (TRFM control software and C8 signal controller firmware) were updated according to the changes on the PRG and PRS algorithms. In the previous ATSP system, the TRFM control software was embedded in the signal controller at 25th Avenue. As the TRFM PC replaced the 170E controller to perform the field master function, the TRFM software for PC version was developed and installed on the TRFM PC. On the other hand, in the previous ATSP system, the C8 signal controller firmware performed the traffic signal transition after the execution of a TSP command. While in the current ATSP system, PRG optimizes two signal cycles including the signal transition cycle. Therefore, some changes were made to the C8 signal controller firmware so that 170E controllers are capable of executing the transition commands sent by PRG.

4.2.4.4 Cost

As mentioned in previous sections, the ATSP system is very flexible and can fit into different environments with different requirements. It uses existing transit and traffic infrastructures and instrumentation for vehicle detection, thus requiring only very low capital and expansion costs.

Since the ATSP system utilizes the GPS/AVL systems that are already installed on transit vehicles for vehicle detection, there is no additional cost for vehicle instrumentation. The cost at intersections for processing and providing the priority request is about $2,000 per intersection. Note that this estimate is based on the assumption that the expansion is for Caltrans centralized intersections. Another cost item is the cost of maintaining wireless communications, which runs at about $80/month for each field master.

4.2.4.5 Requirements

The prerequisites for deployment of the ATSP system include: 1) transit vehicles that are equipped with GPS/AVL, 2) wireless communications between the vehicles and TSP master computer (located at Caltrans D4 office), and 3) traffic controller firmware modified to execute TSP requests. The communication with the PATH Arterial Lab, shown in Figure 3-27, is for data transmission for the purpose of data logging and evaluation and is not absolutely necessary for the ATSP system to work properly.

4.2.5 Hypothetical Examples

Two hypothetical examples are provided below to compare the potential implementation options and costs for the three different TSP systems.

Hypothetical Example 1

A transportation agency is considering implementing a TSP system. The agency currently manages 100 intersections that use 170E controllers running Bi-Tran 233 firmware in a decentralized traffic control system. There is currently no traffic/bus detection functionality at the intersections. The transit agency has 100 buses in its fleet.

Hypothetical Example 2

Another transportation agency currently has a centralized traffic control system with 170E type controllers running Bi-Trans 233 firmware at 200 intersections. The intersections have inductive loop detectors for regular vehicle detection (i.e., without bus identification function). The transit agency has 300 buses in its fleet.

The implementation paths and estimates of associated costs for these two hypothetical examples are presented in Table 4-10.

Table 4-10: TSP Systems Comparison: Examples

		LADOT Centralized TPS System	LACMTA Decentralized System	VTA Decentralized System
Example 1	**Implementation Path**	Upgrade to a centralized signal control system Upgrade signal controllers to type 2070 Adopt the LADOT software package (i.e., controller firmware, ATCS, and TPS) Instrument the intersections and transit vehicles with proper detection and identification devices	Instrument the intersections and transit vehicles with proper detection and identification devices Upgrade the controller firmware.	Instrument the intersections and transit vehicles with proper detection and identification devices Modify controller software modification for priority functions
	Implementation Cost	Centralized signal control system upgrade: Computer hardware $30 K~$40 K plus cost of upgrading communication system 2070 controllers: $300 K~$400 K LADOT software package: $75 K Bus detection and identification: $500 K ~ $1000 K at 100 intersections; $20 K for 100 buses Total cost: $925 K~$1.53 M plus communication system upgrade	Transit vehicle instrumentation cost: $10,000 x 100 = $1 M Intersection communication equipment: $300K~$500 K Signal controller software upgrade: $50 K~$70 K for 100 intersections Total cost: $1.35~1.57 M	Bus detection and identification: $500 K~$1000 K at 100 intersection; $150 x 100 = $15 K for 200 buses Software development cost: $2,500 Total cost: $518 K~$1.02 M
Example 2	**Implementation Path**	Upgrade signal controllers to type 2070 Adopt the LADOT software package (i.e., controller firmware, ATCS, and TPS) Change the detection cards in the control cabinets; equip transit vehicles with transponders	Instrument the intersections and transit vehicles with proper detection and identification devices Upgrade the controller firmware	Change the detection cards in the control cabinets; equip transit vehicles with transponders Controller software modification for priority functions
	Implementation Cost	2070 controllers: $600 K~$800 K LADOT software package: $75 K Detector cards upgrade and transit vehicle instrumentation: approximately $30 K for intersections (detector cards) plus $60 K for 300 buses Total cost: $765 K~$965 K	Transit vehicle instrumentation cost: $10,000 x 300 = $3 M Intersection communication equipment: $600 K~$1 M Signal controller software upgrade: $100 K~$140 K for 200 intersections Total cost: $3.7 M~$4.14 M	Detector cards upgrade: $600 x 200 = $120 K Transit vehicle instrumentation: $150 x 300 = $45 K Software development: $2,500 Total cost: $167.5 K

4.2.6 Summary and Conclusions

Four different TSP system implementations were reviewed and discussed in the previous sections. A centralized TSP system would require real-time communications between a center, where TSP strategies are determined, and field, where TSP strategies are implemented. In a decentralized TSP system on the other hand, the TSP decisions are made locally at the intersections. Thus, the requirement for real-time communication links between intersections and a central location can be avoided. Thus, decentralized TSP systems allow a lot more implementation opportunities, especially in decentralized signal control systems, which lack the real-time communications link.

Two decentralized TSP systems were reviewed. The first one is the implementation along Crenshaw Boulevard in LACMTA's Metro Rapid Bus Program and the second one is the VTA implementation along El Camino Real. Although both systems are decentralized, they differ greatly in terms of transit vehicle detection, vehicle to intersection communications, and signal controller and system software.

Also reviewed was an adaptive TSP system, which provides priority to transit vehicles if warranted while trying to balance the tradeoff between bus delay savings and the impacts on the rest of the traffic. This system utilizes a GPS/AVL system instrumented on buses to continuously monitor bus locations and predict bus arrival times to intersections, and makes real time decisions adaptive to the movements of transit vehicles, traffic conditions and signal status. The system is built upon closed-loop signal control systems with 170E controllers; thus, it may have potential for wide-scale implementation.

Table 4-11 provides a comparison of the TSP systems reviewed. As shown in the table, these three systems all have distinctive requirements for various system components, including transit vehicle detection, communications system, type of signal control system, traffic signal controller, traffic signal controller firmware and software, etc. The table also provides a summary of the benefits and draw-backs of each system, as well as the implementation status and potential.

Table 4-11: TSP Systems Comparison: A Summary

		LADOT Centralized TPS System	LACMTA Decentralized System	VTA Decentralized System	ATSP System
General	**General Description of the System**	Uses newly installed loop detectors, vehicle transponder, and upgraded detector card for bus detection and identification; The TPS software requires 2070 controllers with LADOT firmware and ATCS in a centralized control system; Centralized TSP requires real-time communication between field equipment and central location (TMC).	Uses a GPS-based on-bus system and WLAN communication for bus detection and identification; Four different types of controller firmware have been modified to provide priority functionality.	Uses existing advance and presence loop, vehicle transmitter, and upgraded detector card for bus detection and identification; TSP decision is made at local controller, thus only controller software needs to be enhanced to provide priority treatment according to priority logic.	Uses GPS/AVL system instrumented on buses to continuously monitor bus locations and predict bus arrival times to intersections, and makes real time decisions adaptive to the movements of transit vehicles, traffic conditions and signal status. The system is built upon closed-loop signal control systems with 170E controllers, thus it may have potential for wide-scale implementation. TSP decision is made at a central location, while local controller firmware needs to be updated to execute TSP decisions.
Functionality	**Bus Schedule Adherence Check**	Central TPM software	On-bus system and signal controller	On-bus AVL system (planned)	
	Communication between Buses and Controllers	Hard-wired interconnect	WLAN Spread spectrum radio	Hard-wired interconnect	Wireless GPRS
	Grant Priority	Central TPM software	Local controller	Local controller	Central TSP computer
	Implement Priority	Local controller	Local controller	Local controller	Local controller
	Communication between Controllers and TMC	Required	Not required	Not required	Required
	Central Monitoring Capability	Yes	Yes (for system evaluation purpose, not a function requirement)	Yes (for system evaluation purpose, not a function requirement)	Yes
Components	**Bus Detection and Identification**	Loop detectors, vehicle transponder, and detector card	On-bus GPS based system and WLAN communications	Existing advance and presence loops, vehicle transmitter, and detector card	GPS/AVL system on transit vehicles
	Signal Control System	Centralized control system running ATCS	Decentralized system	Decentralized system	Centralized system
	Signal Controller/ Controller Firmware	2070 w/ LADOT firmware	170E w/ LACO-4 170E w/ Bi-Tran 233 2070 w/ LADOT 2070 firmware Econolite ASC/2	170E w/ Caltrans C-8	170E w/ Caltrans C-8

		LADOT Centralized TPS System	LACMTA Decentralized System	VTA Decentralized System	ATSP System
Benefit & Draw-back	**Benefit**	The TSP decisions are made at a central location, which potentially allows better coordination among different priority requests and better signal priority strategies	Uses GPS for vehicle location and WLAN for communication between vehicles and intersections. Have the potential to utilize other ACS already available on the vehicle.	An economical approach for TSP implementation.	Could provide a very cost effective approach for TSP system expansion since no additional equipment/cost is needed on transit vehicles Benefit for transit vehicles and impact on other traffic could be balanced by adjusting the objective function of the signal timing model.
	Draw-back	Strict requirements on signal controller, controller firmware, and communication system make the system hard to adopt	The current on-bus system is expensive ($10,000 per bus).	Current detector locations are typically less ideal, new loops can be expensive to install, and can also require significant maintenance effort.	More research and testing needed for larger scale implementations
Implementation Examples	**Number of Corridors**	15 corridors in LA	1 corridor in LA County, 33 intersections.	1 corridor in Northern California, 28 intersections.	1 corridor in Northern California, 7 intersections.
	Commercial Readiness	Yes, but may have a very limited market	No	No	No

4.3 BRT System Evaluation and Transferability of Existing LADOT TSP Technologies

One of the most often-touted success stories in implementation of TSP is the City of Los Angeles Department of Transportation. The LADOT worked closely with the Los Angeles County Metropolitan Transportation Authority to successfully implement a TSP system that helped the Bus Rapid Transit system, the MetroRAPID, recognize their operational goals of reliable service at reasonably short headways.

The LADOT and LACMTA teamed up to develop a TSP software implementation that grants priority to transit vehicles along selected corridors. The system utilizes transponders mounted on the buses that communicate through loop detectors at the intersections to let the signal control system know that a bus is approaching the intersection and requires priority treatment. The priority request is passed from the intersection back to the LADOT control center, where the central system determines if priority should be granted based on the headways between successive buses. If priority is granted, the central system software relays the appropriate control commands to the local 2070 intersection controller.

The following sections describe the three primary factors used to determine whether the LADOT Transit Priority System software can be transferred to other locations. The three factors include: 1) controller hardware and software, 2) signal system communications, and 3) system capabilities.

4.3.1 Controller Hardware and Software

The signal controller hardware is a significant issue that must be considered when determining whether the LA Transit Priority System is transferable. A survey of several agencies was completed as a part of this effort. The survey showed considerable variability in the controller hardware used. Responses included 170, NEMA TS2, 2070, and 2070 Lite controllers. Only Los Angeles used the latest generation of 2070 controllers, while all other systems used one of the other controllers. Several agencies indicated that they had (or would have) to change their controllers in order to achieve transit priority. This switch is not trivial for a traffic engineering agency from both an operations and maintenance perspective.

One of the major differences between the various controller types is that the type 170 and 2070 controllers are part of an open architecture (where the controller is independent of the software), while the NEMA controllers are not. The NEMA controllers, as well as the "Lite" 2070's, normally use software that is specific to the hardware manufacturer that built the equipment.

The LADOT TPS software is only transferable to systems using fully-capable 2070 controllers and is not compatible with NEMA TS2 systems or Type 170 systems. Because of this, no other agency that was surveyed as a part of this effort was ready to use the LADOT software. This is one reason why the market for the LADOT Transit Priority System software is limited. This will be less of an issue over time as the 2070 standard matures and costs per controller are reduced.

4.3.2 Signal System Software and Communications

The LADOT system utilizes a robust communication system that is unparalleled by most of today's signal systems. Many of the control systems now being utilized throughout the country use a decentralized or hybrid control strategy, where control decisions are made either at the intersection level, or at an intermediate level of a field master controller that is responsible for maintaining coordination among a group of intersections. In many of these systems, communications to the central site from the field either do not exist or do not occur in real time but have some latency. This prevents transit priority control decisions from being made at the central level (in many cases) since the priority call is not received in a timely fashion at the central site. By the time the priority request makes it to the central site, the central system decides what to do, and transmits the message back to the local intersection controller, the bus may have already been serviced. Thus, when implementing TSP in decentralized signal control systems, the decision of whether or not to grant priority may be made at the local level (between the bus and the traffic signal), which makes decentralized TSP easiest to implement.

Based upon this assessment, the number of systems that would be able to directly implement the LADOT system is limited. LADOT's system is dependent on real-time communications between the local controller and the central computer on a second-by-second basis. The majority of the decentralized or hybrid traffic management systems that are currently installed do not offer the level of communications necessary for the implementation of a central TSP control strategy.

4.3.3 System Capabilities

In all of the TSP systems that have been studied, the particular capabilities that were implemented reflect the operational decisions made by the transit and traffic agencies, or the constraints imposed by existing hardware and/or software. LADOT made a decision that transit priority decisions would be made at the central system level, based on measured headways between transit vehicles. Other systems have successfully implemented transit priority that is unconditional and decided at the local intersection level. Portland, for instance, had decided that they want to favor transit as a matter of practice. This places a higher priority on transit all of the time and fits into Portland's vision for their transportation future.

4.3.4 Conclusions

The variety among the implementations of TSP suggests that it is difficult to implement when in reality it is operating in a wide array of environments. The TSP system often is added into an existing signal system. In many cases, transit priority is not one of the primary considerations when procuring a signal system upgrade; but with proper participation by a transit agency, the traffic signal system managers may build in specifications that may provide an opportunity to incorporate many of the features described previously and some of the LADOT system elements.

One of the objectives of this document, is to identify any transit agency or BRT system that has shown an interest in implementing TSP based on the LADOT's TSP system. LADOT has contracted with the McTrans Center at the University of Florida to distribute their signal control system software. However, to date, there have been no orders for the system. Thus, it would appear that the market for LADOT's system is very small. Very few systems have the processing capability to make real-time priority decisions from a centralized location.

Miami-Dade County, Florida was thought to be a possible candidate for adopting the LADOT system. However, the Miami-Dade signal system is being upgraded, and it does not appear that the upgrade will be compatible with the LADOT system. Miami-Dade has decided to maintain its 170 controllers, rather than the 2070 that LADOT is currently using.

Based on differences in the hardware, software, and system capabilities of various systems, it is not recommended to actively pursue a direct implementation of the LADOT system. The LADOT system was tailor-made by LADOT programmers to fit the needs of their specific system.

4.4 Elements Required for NTCIP 1211 Implementation

This section provides a summary of the importance of the NTCIP standard in developing a transit signal priority system. It discusses the changes necessary to address strategic traffic signal control issues such as transit signal priority. Resolution of significant issues, such as improved ability to request priority on a conditional basis and to balance conflicting requests, will lead to more sustainable solutions that will be more palatable for traffic engineering applications.

The ability to incorporate a standard like NTCIP 1211 into TSP deployments has thus far been limited because of systems incapable of conforming to the standard. There are various limitations of each individual system because the original design was completed without identifying the need for external non-proprietary communications. These limitations are found in systems as diverse as the on-board transit system AVL computers, the detection and communication methods between the transit and roadside systems, and the capabilities of the traffic control system. Typical practice results in upgraded equipment, one piece at

> Most modern traffic signal controllers rely on ***contact closure,*** or an on/off status, for inputs and outputs. As a result, controllers are unable to use enhanced data inputs for making decisions.

a time. For instance, many of the transit vehicle detection technologies currently deployed in TSP applications (e.g., optical, AVI loops, RFID) are limited to the transmission of a simple identification or classification number. Even if the transit vehicle detection technology was capable of transmitting a richer message, most of the traffic signal controllers in use today would not be capable of receiving or processing such a message, as most controllers are limited to simple contact closure inputs and outputs. In many cases, these transit signal priority systems are first-in, first-out (FIFO) systems that are not capable of prioritizing requests. The NTCIP 1211 standard defines the need for an intermediary priority request server (PRS) to translate the request messages into a simple contact closure signal.

Another limitation of the existing systems in place today is the available communications infrastructure and the need for real-time data transfer. The definition of "real-time" can vary in the transit industry based on application rather than a standard set of terms. For instance, real-time passenger information at a bus stop can utilize information from an AVL system that is updated every 30 to 90 seconds. However, in TSP systems, certain portions of the system require resolution less than one second to be effective.

Although many TSP implementations have historically been limited by existing systems, technology has advanced such that opportunities exist for a full implementation of the NTCIP 1211 standard. Implementation under the NTCIP 1211 standard would enable an advanced, conditional TSP system that met the following functional requirements:

- Detect priority vehicles through a TSP detection system
- Relay signal priority requests to a priority server through NTCIP 1211 pathways
- Only grant priority to particular transit vehicles in need of the additional green time or early return to green, based on lateness and other factors
- Terminate the signal priority request once the bus has cleared the stop bar/intersection, and resume normal signal operations as soon as possible (coordination should be retained)

The ability to implement and maintain TSP under the NTCIP 1211 standard lies in the ability to provide the following processes:

1. "Smart" requests generated by the transit system
2. "Smart" decisions made by the traffic control system
3. Feedback mechanisms between the systems

The following sections describe each of these three processes.

4.4.1 Generation of "Smart" Request

The incorporation of "smart" requests into a TSP system is dependent on the ability of the system to: 1) generate a request with sufficient information to make an intelligent decision, and 2) communicate that request to the entity making the decision.

The generation of a "smart" request would enable a TSP system to resolve conflicts between competing transit priority requests and implement an improved TSP solution. Compliance with the NTCIP 1211 message set would enable a "smart" request message. The generation of this message may occur on board the vehicle or at a central management center[6]. Either way, the PRG must be capable of receiving the information necessary to compile a NTCIP 1211 message. The necessary components of the transit system will vary depending on the nature of the desired priority scheme and may include:

- **Real-time interface with the AVL system** -- to provide priority only when a transit vehicle is late, and for selection of the bus that needs the priority, i.e. particularly during competing requests
- **Historic interface with the AVL system --** to make available information about bus travel speed projected down the approach to the stop bar
- **Data inputs provided by the on-board APC** -- to incorporate person delay criteria into the system to compare single occupancy vehicle impacts or competing transit demands
- **Input from the vehicle's speedometer --** to improve the prediction of the vehicle's arrival at the stop bar
- **Connections to the stop request pull cord --** to eliminate requests in advance of a near side stop

Integration of these types of inputs from the various components will contribute to the development of a NTCIP 1211 message by the PRG. For instance, use of real-time information from the AVL system would allow the PRG to determine vehicle location relative to the signalized intersection network. This system will identify the transit vehicle and indicate if the vehicle is on-route and within signal priority jurisdictional boundaries. To enable conditional priority, the AVL system must interface with scheduling software/databases to compare actual bus location to the bus's schedule. Input from the AVL system would then be used by the PRG to develop a request only for a vehicle that is late by some defined threshold. Ideally, the request would incorporate relative degrees of priority, based on the amount of lateness, to address competing calls for priority. Relative need for priority between multiple requests can also be defined in a NTCIP 1211 message based on input from a vehicle's on-board automatic passenger counter (APC). Using current vehicle occupancy data from an APC, the *Class Level* object can be modified to prioritize multiple requests for priority at an intersection. Incorporation of APC data would enable the TSP algorithm to consider overall person delay in the control decision. Of course the APC is unable to determine how many passengers are waiting at downstream stops and whether priority would be warranted based on reduction of delay to these passengers.

It is also important that the system enables the generation of update messages to prevent inefficient use of priority in an environment that is dynamic and can be highly variable. For instance, if the PRG receives data inputs from the vehicle's speedometer, the PRG may be capable of improving and modifying the prediction for the *Desired Time of Service* object. Other modifications to this object could be made by providing connections to the vehicle's stop request pull cords or door sensors to identify a transit vehicle's travel time being affected by the need to service a patron at a near-side stop. A

[6] Earlier reports on Task 6 highlight the challenges of communication within the various implementation scenarios.

PRG that is capable of generating update messages will enable a more efficient TSP scheme.

Table 4-12 outlines each of the NTCIP 1211 objects included in the message from the PRG to the PRS. For each object, an example of how that object could be used in the generation of a "smart" request has been identified.

Table 4-12: Use of NTCIP Message in the Generation of a "Smart" Request

Object	Function	Example Use
Priority Request ID	Unique identifier assigned by the PRG to identify a particular priority request	Provide feedback and monitoring mechanism
Priority Request Vehicle ID	Unique identifier for vehicle (typically VIN)	Validate vehicle as authorized transit vehicle
Priority Request Class Type	Relative priority of request on scale of 1- 10 (1=highest, 10=lowest)	Give preference to differing levels of transit (e.g., BRT over local bus)
Priority Request Class Level	Relative priority within each class on scale of 1- 10 (1=highest, 10=lowest)	Determine preference when presented with multiple calls based on degree of lateness or ridership
Priority Request Service Strategy Number	PRG requested strategy	Use alternate priority routine for near-side stops
Priority Request Time Of Service Desired	Estimated time of arrival at the intersection	Provide ETA for PRS to determine duration of priority necessary
Priority Request Time Of Estimated Departure	Estimated time of departure from the intersection	Provide estimate for bus departure from intersection and return to normal operations

The strength of the NTCIP 1211 message definition is the flexibility permitted in developing values for each of the objects. The example uses are meant only to provide a general understanding of how each object might be used. The actual use of each object is quite flexible and is dependent on the desired priority scheme and the available inputs to the PRG.

4.4.2 Communication of "Smart" Request

The second component necessary to produce a "smart" request is a communication medium capable of transmitting a message with multiple data objects. As mentioned previously, many of the message transmission technologies currently in use are limited to the communication of nothing more than an identification number. More advanced technologies, such as 802.11 WLAN and Dedicated Short-Range Communications (DSRC) afford the opportunity to transmit more complex messages and are able to continually provide update messages as a vehicle approaches an intersection. Although the individual NTCIP message requires relatively little bandwidth for transmission, network bandwidth availability and message latency must be still be considered.

4.4.3 Opportunities for Test Deployments of "Smart" Request

As mentioned previously, an essential component for implementation of a TSP system based on NTCIP 1211 messages is the ability to transmit those messages from the transit system to the traffic control system. For instance, a system based on wireless communication, such as the system deployed by LACMTA, provides the opportunity to send messages with multiple objects. Table 4-13 shows the objects currently being sent in the LACMTA message as well as some of the comparable NTCIP 1211 objects.

Table 4-13: LACMTA Message Set

Field	LACMTA Message Object	Similar NTCIP 1211 Object
1	Start Flag	
2	Address Packet, Variable Length (1-3 bytes)	Priority Request ID
3	Control (send data no response)	
4	Initial Protocol Identifier (IPI)	
5	Command (0x80 STMP + 0x05 Bus Status with N Data bytes; N=5 for Pilot Project Protocol, N=8 for Metro Rapid Protocol)	Priority Request Service Strategy Number
6	Protocol Revision (R=1 Pilot Project Protocol; R=2 Metro Rapid Protocol)	
7	Data, Bus Identifier (two bytes) MSB, LSB	Priority Request Vehicle ID
8	Data, Bus Status	
9	Data, Bus ETA	Priority Request Time Of Service Desired
10	Data, DTGP Action	
11	Scheduled Headway (one byte) – Metro Rapid Protocol Only	
12	Bus Route (two bytes) – Metro Rapid Protocol Only	
13	CRC (two bytes) MSB, LSB	
14	End Flag	

The LACMTA message set already contains some objects that closely resemble objects defined by NTCIP 1211. A test deployment of the NTCIP 1211 message set could be achieved with a modification of the LACMTA message set or a deployment based on this model.

4.4.4 “Smart” Decisions

Once the PRG generates and transmits the standard message, the PRS must be capable of receiving the message and implementing a decision based on the content of the message. Ideally, the PRS would be internal to the traffic control system, either as part of the central system or the local controller. If the traffic control system is capable of receiving and acting upon a NTCIP 1211 message, the message could then be interfaced with other standard NTCIP protocols (i.e. NTCIP 1202) to enable more intelligent decisions to be made. For instance, the traffic control system could use information such as queue lengths or side-street demand volumes in the decision making process. The following characteristics should be present in a traffic control system capable of receiving NTCIP 1211 messages:

- Process data from priority detection system and conditional priority logic to determine if and how much priority should be granted at the local intersection
- Capable of processing and prioritizing multiple requests for priority and prompting the local controller to carry out the most critical function (e.g., a bus 60 seconds late over one 10 seconds late)
- Override all priority requests when a preemption request is registered
- Log all priority/preemption activities; this should include logging the signal status at the time when priority requests are received
- Develop an optimized priority/preemption solution based on signal priority inputs and logic
- Transition back to normal signal operations as soon as possible once priority/preemption vehicle has left the intersection
- Accept and process input from the traffic signal system related to queuing
- Accept update messages related to prediction of the bus arrival at the stop bar of the TSP intersection

If the traffic control system is not capable of accepting a standard message, it would be necessary to process the message using an external PRS. This external PRS would then provide a signal to the traffic control system requesting priority. This signal would be limited to the contact closure currently being used by most traffic signal controllers. This would require the processing and prioritization of multiple messages to occur outside the traffic control system. Furthermore, once a decision by the external PRS was made to request priority for a particular phase, it may not be possible to modify or cancel that request based on updated messages received from the PRG. Also the use of an external PRS would limit or possibly even prevent the incorporation of traffic data into the decision-making process. Therefore, it is recommended that an agency seeking to implement TSP based on the NTCIP 1211 standard work with traffic signal controller manufacturers to enable controllers to accept and process NTCIP messages.

It is important that controllers be able to not only accept one message but accept multiple messages and updates to those messages. As previously mentioned the use of update messages allows the system to maximize efficiency in a dynamic environment. For instance, consider the scenarios described in the following three case studies.

Update Message - Case Study 1

Consider the scenario shown in Figure 4-28. A bus is approaching a TSP intersection and is detected on the major street at t = 0s. At that point, the estimated time of arrival (ETA) for the bus at the stopbar is t = 20s. The normal end of green for this major street phase is t = 5s and the next start of green is 50s, assuming a cycle length of 100s. A message with the bus ETA is sent to the controller, which begins looking for opportunities to provide priority to the major street, in this case a green extension that would result in no bus delay (e.g., an extension to t = 21s).

However, ten seconds after the bus is detected (t = 10s) the bus is delayed and reports an ETA of t = 30s[7]. Without an updated ETA from the bus, the controller would have to assume, based on the original ETA for the bus, that the bus will arrive at the intersection at t = 20s and the green extension for the bus will end at t = 21s. With application of a NTCIP 1211 update message, the controller could change plans and, instead of extending the green for the bus, the controller could resort back to the normal operation by ending the green immediately. By using this additional message, impacts to side street traffic would be minimized and the resulting delay for the bus may be reduced by 11 seconds.

Update Message - Case Study 2

Figure 4-29 shows another situation in which it would be desirable to have an update message. Two buses are approaching a TSP intersection from different roadways. Bus A is detected on the minor street at t = 0s. At that point, the ETA for Bus A at the stopbar is t = 20s. A message with this ETA is sent to the controller, which begins looking for opportunities to provide priority to Bus A. Ten seconds later (t = 10s) Bus B is detected on the major street and reports a travel time to the stopbar of 15 seconds (ETA at t = 25s). In the meantime, Bus A has stopped at a near-side transit stop and has an updated ETA of t = 30s. However, without an update message from Bus A, the controller would have to assume, based on the original ETA for Bus A, that Bus A will arrive at the intersection (t = 20s) prior to Bus B (t = 25s). If Bus A had transmitted an update message indicating the new ETA, the controller may have been able to change its control decision and service the Bus B request first. The result could be a minimization of the overall delay for transit passengers.

[7] This could be a result of traffic congestion or a requested stop at a nearside bus stop

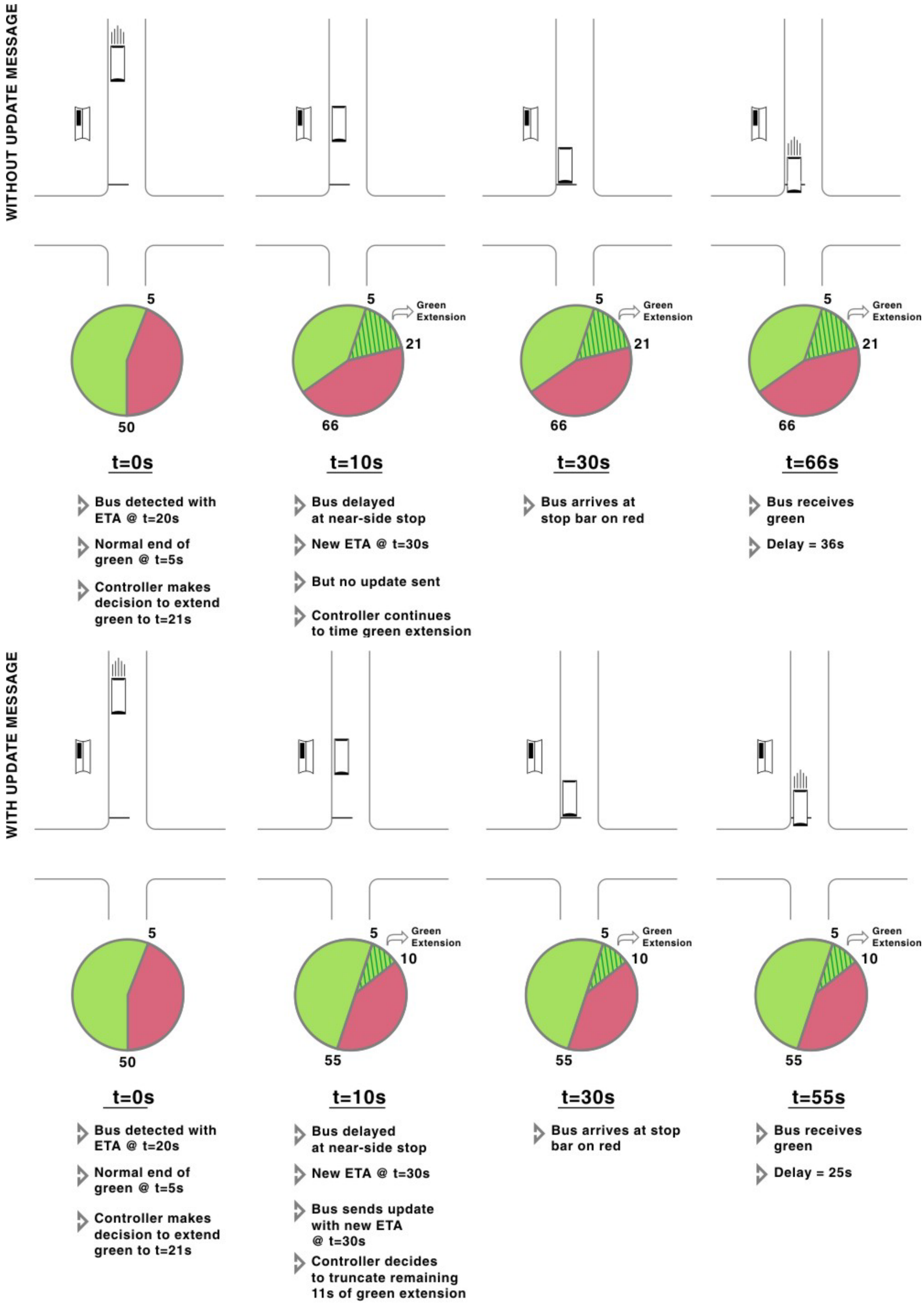


Figure 4-28: Use of an Update Message – Case Study 1

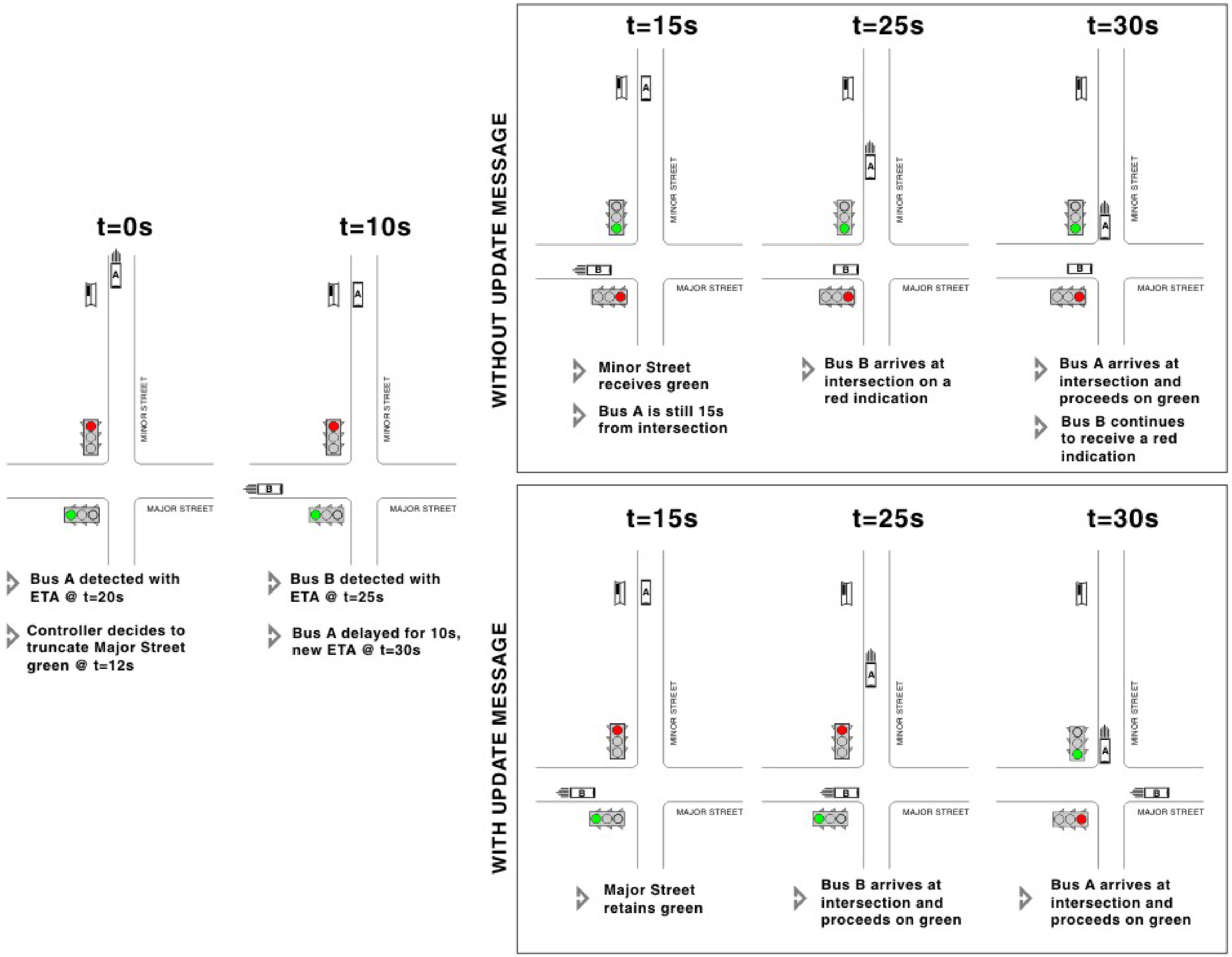


Figure 4-29: Use of an Update Message – Case Study 2

Update Message - Case Study 3

In this example, consider two buses approaching an intersection on intersecting roadways. Bus A is detected first and reports being late by 30 seconds. The controller begins to look for an opportunity to provide priority to Bus A. However, a few seconds later, Bus B is detected and reports being late by 120 seconds. It may be desirable to abort the decision to provide priority to Bus A, and instead consider Bus B to be the priority vehicle at the intersection. However, most existing TSP applications, with the absence of an update message, resort to a first-in, first-out policy in this situation. Therefore, the vehicle with the greatest need may not be the vehicle that receives the most benefit and, in fact, may be penalized by a control decision that can't consider opposing requests for priority.

For the reasons outlined in these three case studies, and other reasons not mentioned here, the use of update messages is vital to the efficient use of transit signal priority. The allowance for the transmission and processing of update messages will be an important advancement in the state-of-the-practice of transit signal priority.

4.4.5 Feedback Mechanism

Feedback from the TSP system is the component most often overlooked in TSP deployments. Feedback from both the signal system and the transit system is critical to monitor the effectiveness of TSP. After deploying a TSP system, it is important for both the traffic and transit agencies involved to establish performance measures that define the effectiveness of the system in carrying out the desirable policies. Without a feedback mechanism, agencies are unable to assess the performance of the system. Furthermore, a feedback and monitoring mechanism enables system operators to identify and address problems as they arise. Due to the transparent nature of TSP, many problems may go undetected without the ability to monitor requests and the responding actions.

4.4.6 Performance Measures for Evaluation

There are three main aspects of TSP operations that require evaluation:

- Technical Performance (Is the selected technology working as expected?)
- Bus Operations Performance (Is TSP providing measurable benefits for buses and passengers?)
- Arterial Operations Performance (What are the impacts of TSP on other roadway users?)

Many of the following performance measures are useful both for initial before-and-after testing and for continued monitoring of the effectiveness of a TSP system.

Technology Performance

This portion of the evaluation focuses on whether the communication links assumed in the TSP Market Package are working as planned, and whether all of the essential components of TSP technology are functioning as designed. Specific questions that should be answered include:

- Are TSP requests being correctly generated? Is there any latency of messages between system components that negatively impact performance? Are the data formats consistent with the standard messages?

- If conditional priority is being used, are the conditions used to determine whether TSP should be requested or granted being evaluated accurately, reliably, and in a timely manner?
- What percent of the time is a TSP request made, if conditional priority is used to generate requests? What percent of TSP requests are granted? What are the main reasons for requests not being granted?
- How reliable are the components of the TSP system (what percent of the time is TSP inoperative due to a problem with one of the essential components)? What are the main causes of any identified problems?

Bus Operations Performance

This portion of the evaluation takes a before-and-after look at the impact of TSP on bus operations, addressing both the passenger and agency points of view. One of the key elements of this evaluation is the need to develop objectives prior to the implementation of TSP. Aspects of bus performance that are impacted by TSP and that can be quantitatively evaluated include:

- Schedule and headway adherence
- Travel speed and travel time
- Travel time variability (e.g., coefficient of variation of travel times or the 85th-percentile travel time)

Arterial Operations Performance

This portion of the evaluation looks at the before-and-after impacts of TSP on roadway operations, specifically looking at impacts to motorists, impacts to buses, and combined impacts to all roadway users. Aspects of arterial performance that are impacted by TSP and that can be quantitatively evaluated include:

- Change in bus delay, by intersection
- Change in bus travel time in corridor
- Change in auto delay, by intersection
- Change in auto travel time in corridor
- Change in person delay, by intersection and overall
- Change in hourly auto throughput
- Change in the number of cycle failures, by approach

A qualitative aspect of arterial operations that can be tracked is the change in number of complaints that traffic signal operators receive about the performance of intersections where TSP is implemented. As a control, changes in the number of complaints received about non-TSP intersections should also be tracked.

4.4.7 Data Sources

On-Board Technology

At a minimum, the AVL equipment incorporated into the TSP system should provide bus arrival and departure times at each stop (e.g., the times the bus breaks a 30-m/100-ft circle around the stop location[8]) and average speeds between stops, as shown in Figure 4-30. Ideally, AVL should also provide door-opening and door-closing times at stops, so that dwell time can be separated from traffic signal delay during evaluation. Each data record should also provide the bus ID number, driver ID number, and schedule block number.

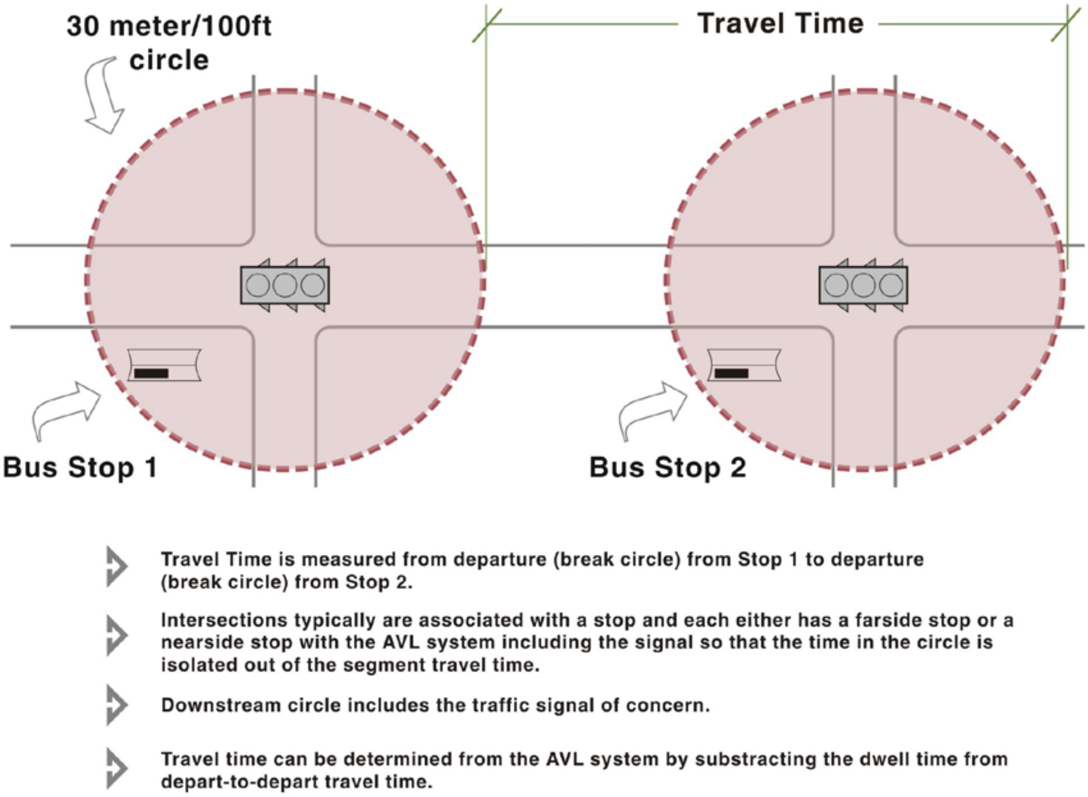


Figure 4-30: Sample Segment Analysis Using AVL System

If available, APCs should be used to gather passenger load data, which would be used in evaluating bus passenger person-delay. Ideally, the APC unit would be integrated with the AVL unit, and would add the following fields to each bus stop data record: passengers on, passengers off, and load departing each stop.

TSP Request Generator/Server Logs

Logs created by the TSP request generators and servers should be used to evaluate TSP technology performance. Assuming conditional priority, the request generation log should create a record each time the TSP equipment is turned on or off, containing the following fields: the bus ID number, the driver ID number, the schedule block number, the bus location (from the AVL system), TSP status (on or off), the time the record was generated (from the AVL system), and information about the conditions at the time the

[8] The suggested 30-meter/100-foot circle provides a margin of error for determining when a bus arrives. The bus stop may not be geocoded exactly in the correct position, the AVL device samples the bus' location only once a second, the global positioning system (GPS) accuracy may not be ideal (depending on the number of satellites in view, signals bouncing off of buildings, etc.), and so on.

TSP status was changed (e.g., schedule status, passenger loads). The data reports should utilize the standard messages presented in the SAE J1587 standard.

The TSP request may be served within the traffic signal controller cabinet. In this case, the server logs will need to be downloaded from each cabinet, by staff of the agency or agencies owning the signals. Ideally, this download would occur without direct intervention from the signal engineer because communications between the central system and the controller exist. The server log should include the following: time the request was received, the bus ID number (if passed to the server), information on where in its cycle the traffic signal was when the request was received, and a code indicating how the request was processed (e.g., green extended, red truncated, no action taken). If a check-in/check-out system is used, the log should also include the time the check-out signal was received. In the unlikely event that schedule data are stored with a local TSP server for use with conditional priority, the log should also provide the stored scheduled arrival time, and bus AVL data should be obtained to compare the two clocks.

The TSP request might also be served at a central location. In this case, a single log would be obtained from the agency responsible for the TMC. The log should include the following: location at which the request was received, the time the request was received, the bus ID number (if passed to the server), information on where in its cycle the traffic signal was when the request was received, and a code indicating how the request was processed (e.g., green extended, red truncated, no action taken). If conditional priority is processed centrally, the log should also provide information relating to the conditions checked (which might be stored at the TMC or received via a communications link with the transit agency).

Table 4-14 provides example data elements, their source, and the performance measurements that could be derived from the data elements.

Table 4-14: TSP Data for Evaluation

Data Element and Source	Measures of Effectiveness
Scheduled vs. Actual Time at Time Points (AVL System)	Average transit travel speed
	Average transit trip time
	Statistical variability in travel time
	Percentage of buses arriving on time
	Frequency of "bus bunching"
Bus Occupancy Data (On-board APC)	Transit mode share
	Transit Rides per Capita
	Transit Ridership
Traffic Signal Phase Splits and Event Logs (Signal System)	Average delay for vehicles on side street approaches
	Number of cycles impacted by TSP
	Average impact of Priority Request to intersection
	Maintain minimum phase length for pedestrians
	Conform to driver expectations

A robust monitoring system would provide feedback from both the traffic and transit systems. All requests transmitted by the PRG would be logged. The corresponding response by the PRS would also be recorded and could be compared against the expected response. A time stamp should be associated with both the request generation and the action taken upon that request in order to evaluate latency in the system. The provision of this feedback loop enables operators to improve the effectiveness and efficiency of TSP systems. Addition discussion on evaluating TSP performance, as well as a discussion on TSP modeling, is presented in Chapter 5.

5 Evaluation of TSP Performance

It is important to evaluate the impact of TSP for demonstrating the benefit of a TSP system, to assess its impact on non-priority street general traffic, and to determine the specific conditions under which TSP is most cost effective. A good evaluation will also help determine the future direction of TSP in the transit agency[9].

In reported TSP studies, time savings due to the introduction of TSP vary significantly from implementation to implementation. This large variation is, to a great extent, contributed by the fact that the Measure of Effectiveness (MOEs), the types and quality of the collected data, and the methods used for analyzing the data differ significantly. As a result, the findings of these studies often do not have comparative values. For example, most of the evaluation studies focused on savings in trip time to evaluate the performance and benefits of TSP. Because TSP systems are in many cases deployed in conjunction with other changes, including but not limited to changes of schedules, routes and operation policies, the time savings do not reflect the benefit of just TSP implementation, but also include the results of all the improvements. Furthermore, the data collection methods vary considerably, ranging from manually timing the trip time to using AVL data to compare time points, which also add to the uncertainties on how the data can be compared with each other. In addition, despite the fact that the possible interruption on traffic by frequent TSP calls is a common concern to many traffic engineers, the assessment regarding the negative impacts on traffic has been very limited and the results in many cases are qualitative and subjective.

Because of the reasons listed above, FTA decided to include the study on TSP evaluation approaches under this project. The project team subsequently developed a set of detailed MOEs and a comprehensive evaluation method that can support an objective evaluation of TSP system performance and its impact on traffic. This chapter summarizes the MOEs and evaluation methods and, through evaluation case studies, presented how the MOEs and evaluation methods can be implemented.

5.1 Measures of Effectiveness (MOEs)

There are three components of TSP operations that require evaluation:

- Technology - Is the selected technology working as expected? Is it acceptable based on the specifications developed as a part of the system engineering process? Does TSP increase maintenance costs?
- Transit Performance - Is TSP providing measurable benefits for buses and passengers? What are the effects on reliability?
- Arterial Performance - What are the impacts of TSP on other roadway users (network delay, safety, etc.)?

Measures of effectiveness (MOEs) for transit and arterial components assessment should be quantifiable in the before-and-after condition, and should accommodate monitoring of a TSP system. The improvement of TSP in isolation or in concert with other BRT

[9] Harriet R. Smith, Brendon Hemily, "Transit Signal Priority, a planning and evaluation handbook," published by ITS America, May 2005.

improvements has resulted in increases in ridership. Ridership increases can increase dwell time, which in turn may slow the average speed of the service. It is important to recognize the externalities and isolate for the effects where possible.

The use of MOEs in several existing TSP evaluation studies indicate the following: 1) there is no common set of MOEs, 2) the MOEs are typically well reported at a planning level and ongoing performance measurement is less common, and 3) the studies have not used sufficient MOEs to provide a comprehensive assessment and to isolate particular effects, such as whether a green extension is more effective then a red truncation.

It is also important to recognize that the MOEs used can be stratified by the particular users affected to determine the effect TSP has on the local project objectives. Users or groups that may be isolated include the transit vehicle with TSP, traffic (by approach or for the entire system), and pedestrians. Ideally, the support systems (the traffic management center and the transit management system or AVL system) would be modified to collect data that can be used to summarize the benefits and impacts. As a part of this research, the project team did not find a system that offers full use of the synchronized and integrated transit, traffic signal, and traffic condition data. Table 5-1 presents the recommended set of MOEs. These address reliability, travel speed/time, operating cost, pollutant emission, ridership, safety, and TSP performance for transit and arterial components. With the exception of those in *italics*, a subset may be selected to address a specific audience or issue. Example scenarios include major concerns of local-area stakeholders, significant impacts, limited data, TSP operations, etc.

Table 5-1: Measures of Effectiveness for Transit Signal Priority Systems

Category	Prioritized Transit / Route	Traffic (same direction)*	Minor Traffic (cross-street; protected main-street left turn)*	Passengers on Prioritized Route	Pedestrians
Reliability	1) Percentage of on-time runs at timepoint; 2) average arrival deviation at timepoint; 3) variance of arrival deviation at timepoint; 4) largest arrival deviation at timepoint; 5) variance of segment travel time; 6) number of missing connections at transfer point; 7) variance of total route travel time (results in reduced layover schedule)	N/A	N/A	1) Number of missed connections (transfers): 2) average waiting time at bus stop	N/A
Travel Time / Speed	1) Average travel time on segment and breakdown (dwelling time, intersection delay, running time, etc.); 2) average travel speed on segment; 3) average delay at prioritized intersection (signal delay and other delay); 4) number of stops at red (at prioritized intersection)	1) Average travel time on segment; 2) average travel speed on segment; 3) average delay at prioritized intersection (early green, green extension, and other operations, respectively; average across the impacted cycles only); 4) number of stops at red; 5) reduced queue length	1) Average delay at prioritized intersections (early green, green extension, and other operations, respectively; average across impacted cycles only); 2) number of cycle failures, where a failure refers to the inability of a signal cycle to clear all of the queued vehicles; 3) number of stops at red	1) Average person delay at prioritized intersection	N/A
Operating Cost	1) Average fuel consumption; 2) fleet size requirement; 3) number of operators	1) Average fuel consumption	1) Average fuel consumption	N/A	N/A
Pollutant Emission	1) Average vehicle emission (CO and NOx)	1) Average vehicle emission by class (CO and NOx)	1) Average vehicle emission by class (CO and NOx)	N/A	N/A
Ridership	1) Average passenger occupancy per bus; 2) number of passengers per mile	N/A	N/A	N/A	N/A
Safety	1) Number of accidents (involving buses and signal priority)				1) Number of pedestrian accidents; 2) average reduction of pedestrian walk cycle
TSP System Performance and Signal System	1) Frequency of TSP calls (cycle-based); 2) frequency of TSP executions (cycle-based, early green, green extension, and other operations, respectively); 3) TSP successful rate (early green, green extension, and other operations, respectively), 4) missed coordination steps, 5) effects on bandwidth				

Note: Some of the above MOEs, particularly those in the Travel Time / Speed category, may need to be normalized for variables, such as density of intersections, speed limit of roadway, ridership between before and after study.

* Including non-prioritized buses, autos, and others

N/A = not applicable

5.2 TSP Evaluation for Planning

There are various analysis tools used to evaluate TSP. They can be broken into the following three categories: 1) macroscopic ridership forecasting, 2) macroscopic coarse level traffic analysis, and 3) microscopic detailed traffic analysis. Macroscopic tools use theories that are based on empirical data. One such example is Synchro, which uses the traffic theory developed in the Highway Capacity Manual. Microscopic simulation models, on the other hand, use a random number generator to simulate individual vehicles with different driver behavior. Many elements of Intelligent Transportation Systems (e.g. adaptive control, coordinated traffic signals, TSP, ramp metering, changeable message signs, dynamic route guidance, etc.) can also be modeled in microscopic simulation.

5.2.1 Macroscopic Ridership Forecasting Models

Transit ridership prediction is central to transit planning for several reasons. The most important reasons are: 1) ridership directly measures transit's role in meeting the transportation needs of the community, 2) it directly affects revenue generation, and 3) ridership forecasts are critical elements of service planning (e.g. determining the number of vehicles and drivers needed to provide a certain level of service).

The need for reliable transit ridership estimates also arises when there is significant change in service, such as TSP or changes in fare levels. Social-economic trends may also prompt transit agencies to predict ridership for planning and budgeting purposes.

A great variety of ridership forecast models have been developed over the years. Menhard and Ruprecht (1983)[10] summarized the use of route-level ridership prediction techniques, including professional judgment, surveys, regression analysis, and elasticity-based approaches. The four-step transportation planning model has been used by many metropolitan planning organizations. Mayworm, Lago and McEnroe (1980)[11] and several versions of *Traveler Response to Transportation System Changes* by Pratt et al (1977)[12], (1981)[13], (2004)[14] have been key resources of empirical evidence. Appendix C provides a detailed discussion of these ridership theories and tools.

5.2.2 Macroscopic Traffic Tools

Macroscopic traffic analysis models are often used by traffic engineers to assess the adequacy of intersections for vehicular traffic. The Highway Capacity Manual methodology for signalized intersections is commonly incorporated into these models. This model is limited to consideration and estimation of traffic delays by lane group on

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[10] H. Menhard and G. Ruprecht, Review of Route-Level Ridership Prediction Techniques, Transportation Research Record 936, Transportation Research Board, National Research Council, Washington, D.C., 1983.

[11] P. Mayworm, A. Lago, and J. McEnroe, Patronage Impacts of Changes in Transit Fares and Services, Urban Mass Transportation Agency, Washington, D.C., 1980.

[12] R. Pratt, N. Pederson, and J. Mather, Traveler Response to Transportation System Changes: A Handbook for Transportation Planners, Federal Highway Administration, Washington, D.C., 1977.

[13] R. Pratt, and J. Coople, Traveler Response to Transportation System Changes, 2nd ed., Federal Highway Administration, Washington, D.C., 1981.

[14] R. Pratt et al., Traveler Response to Transportation System Changes, TCRP Report 95, Transportation Research Board, 2004.

each approach. Because of their wide use in the traffic engineering community, there may be data and models available for an initial screening-level evaluation of potential corridors and to evaluate the transit and traffic impacts following TSP implementation. At the screening-level, signal locations are identified based on the following criteria:

- Locations that provide the greatest reduction in delay, typically those intersections with moderate to high delay
- Locations where signal timing is flexible and provides an opportunity to borrow or take time from the non-transit movement
- Depending on the transportation policies of the local area, TSP may be easiest to implement at locations with adequate capacity to allow for TSP signal timing modifications, such that a reduction in the non-transit vehicle green phase does not significantly and negatively impact the delay

Macroscopic models, such as Synchro, can be used to determine the movement delay and volume-to-capacity ratios. It is assumed that these measures reflect the operations of the transit vehicle at the traffic signal, exclusive of the transit stops and dwell time that may result in delays associated with the deceleration and acceleration of a vehicle in and out of the traffic stream. In reality, use of a traffic model for estimation of impacts of transit signal priority is a gross estimation of the conditions, but at an initial screening level is appropriate to identify locations where additional traffic analysis using a simulation model may be appropriate. A sample of an implementation threshold for an agency that wanted to minimize traffic impacts is provided in Table 5-2.

Table 5-2: Delay and Volume-to-Capacity Ratio Thresholds

Opportunity Ranking	Vehicle Delay (sec/veh)	Volume-to-Capacity Ratio
Low	**< 25**	**> 0.90**
Medium	**< 25** **25 – 60**	**< 0.90** **> 0.75**
High	**> 25**	**< 0.75**

An assessment of transit and traffic impacts can be performed using the macroscopic model by increasing the green time that serves the transit vehicle and estimating the resulting effects to delay. The amount of additional green time depends on a variety of factors including operating mode (coordinated operations versus free operations), pedestrian timing, cycle length, signal phasing, splits, and time-of-day.

Application of signal priority in microscopic model requires several assumptions for the assessment. Rather than define location of detection zone and the logic within the signal controller, simple assumptions are made related to the amount of time taken to estimate the effect of TSP. A practical assumption is to take a percentage of the excess time required for non-transit vehicle green time. That is, the excess time above the minimum time needed to serve pedestrian or vehicular demands. For example, if a non-transit vehicle phase has a minimum green time of 20 seconds and a maximum green time of 30 seconds, then the green time reduction is 0.5x(30-20) = 5 seconds.

The resulting MOEs from the analysis include volume to capacity ratios, and intersection and approach delays at the traffic signals. The volume-to-capacity ratio for each cycle should be averaged over the hour. These cycles will include non-TSP and TSP operations depending on the number of anticipated TSP calls. If the average volume-to-capacity ratio is in excess of 1.0, the reduction should be modified and retested to minimize the traffic impacts. Finally, the average movement delay of the transit vehicle with and without TSP can be used to determine the transit-vehicle delay savings.

5.2.3 Microscopic Traffic Tools

Microscopic traffic analysis models are increasingly used by traffic engineers for conducting multimodal assessments. The use of microscopic models requires a significant additional effort beyond the macroscopic models for development and is less likely to be developed for corridors. The models have improved and many are inclusive of modes including transit and pedestrians and can measure the impacts of specific strategies like TSP. One particular application of the simulation tool is testing candidate TSP timing plans and picking the best timing plan.

Smith and Hemily (2005)[15] noted that "microscopic models are able to simulate transit signal priority applications at the individual intersection level", and that

> *Signal control logic and detection are important simulation features necessary for simulating transit signal priority operations. Simulation of TSP requires that simulation models can detect and distinguish between various types of vehicles and their routes, in particular transit vehicles. Modeling transit signal priority requires making changes to the traffic signal control logic of the controller. Many simulation models offer basic TSP features like green extension and red truncation. Users should understand the capabilities and limitations of the model in simulating green extension and red truncation given that traffic signal controllers accomplish these treatments in different ways, including which phases are shortened and whether the time is taken from the current cycle or the next cycle. Users should also understand the capabilities and limitations of the model in simulating advanced features like phase rotation, phase insertion and phase skipping. In addition, the user should know if changes to signal control logic can be done by the user or have to be done by the software vendor, since the latter might be expensive and time consuming.*

Many earlier evaluations of TSP strategies (e.g. Illinois DOT[16], Al-Sahili and Taylor[17], and Garrow and Machemehl[18]) use NETSIM as the micro-simulator. The uses and

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[15] H. Smith and B. Hemily, Transit Signal Priority (TSP): A Planning and Implementation Handbook, ITS America, May 2005

[16] Illinois Department of Transportation. Cermak Road Bus Preemption Study, Summary Report. Civiltech Engineering, Inc. Itasca, IL & JRH Transportation Engineering, Eugene, OR. October, 1993a.

limitations of NETSIM have been discussed in Skabardonis (1998). More recently, VISSIM has been used by Dale et al[19] and Ova and Smadi[20] for evaluating TSP strategies. VISSIM contains a simulator and a signal state generator. Users of VISSIM can analyze impacts of different signal operations such as fixed time, actuated, and adaptive TSP. In particular, users can define signal control logic through VISSIM's VAP language logic, and VISSIM provides an interface to various signal controller firmware. These features make VISSIM well suited for evaluating TSP strategies. VISSIM can report multiple MOEs for an individual vehicle, thus transit agency managers could evaluate the effectiveness of TSP.

FHWA's NGSIM aims to develop a core of open behavioral algorithms with supporting documentation and validation data sets that describe the movement and interaction of multi-modal travelers and vehicles on the roadway system and their interactions with traffic control devices, delineation, congestion, and other features of the dynamic traffic environment. Appendix D discusses efforts and opportunities to promote transit and TSP representation in NGSIM.

5.2.4 Using Micro-simulators to Evaluate Secondary TSP benefits

Improved service to transit riders and increased transit ridership are primary objectives of TSP. While micro-simulators can be used to evaluate transit service improvements, they are not designed to predict transit ridership. However, micro-simulators can be used to evaluate several secondary benefits of TSP, such as reduced wear and tear of equipment, less pavement maintenance and reduced emissions due to reduced stops. As long as a good cost-allocation model is available so that cost per stop can be estimated, the procedure for evaluating secondary benefits of TSP is rather straight-forward.

However, the estimates obtained from using micro-simulators do not fully account for the benefits, mainly because the ridership and modal split impacts are not included. Mesoscopic econometric models and macroscopic demand forecasters are needed to address ridership and related impacts.

5.3 TSP Operations Evaluation

TSP can be an effective method for improving transit service, efficiency, and reliability in spite of increasing congestion; however, it is only a method. Unless the results of this method are measured and evaluated, the system will never truly contribute its maximum potential benefit. Ultimately, the goal of TSP is to improve transit performance, which

[17] K. Al-Sahili and W. Taylor, "Evaluation of Bus Priority Signal Strategies in Ann Arbor, Michigan," Transportation Research Record 1554. Washington, D.C. 1996.

[18] M. Garrow and R. Machemehl, Development and Evaluation of Transit Signal Priority Strategies. Southwest Region University Transportation Center, Report No. SWUTC/97/472840-00068-1. August 1997.

[19] J. Dale, T. Bauer, R. Atherley and L. Madson, A Transit Signal Priority Impact Assessment Methodology—Greater Reliance on Simulation, 78th Annual TRB meeting, Washington D.C., January 1999

[20] K. Ova and A. Smadi, Evaluation of Transit Signal Priority Strategies for Small-Medium Cities, December 2001

means transit operations must be measured and compared. Given the wide range of potential uses for TSP, from local routes to bus rapid transit, understanding how TSP affects the performance of a system is requisite to maximizing the benefit of that impact. The primary aspects of transit service that are affected by TSP are travel time/speed and reliability. Four primary performance measures that can be used to determine travel speed and reliability are:

- Average speed
- Statistical variability in travel time
- Percentage of buses arriving on time
- Frequency of "bus bunching"

Understanding the effects of TSP is a challenge due to a variety of factors, such as driver behavior, ridership, and traffic conditions, which can considerably affect transit performance. Measuring the effect of TSP requires a careful understanding of how these other factors effect traffic flow, so that improvements can be attributed to the correct factor. The type of data recorded and the resolution (how often the data are recorded) are central to accurately measuring the effect of TSP. Not only are many types of data required, but these data must be collected frequently and stored in an organized fashion.

5.3.1 Use of Transit Management System Data for Transit Performance Assessment

The measurements described above can be collected by technology on board the bus, which may include APCs, AVL, Farebox and others. To give a complete picture, measurements should be recorded for bus performance over the entire course of the route and individual intersections. The more frequently data are sampled, the more accurate these calculated values become, improving the chances of isolating the TSP characteristics. Devices commonly installed on buses that record data and that can be used to calculate performance measures include:

- **Automatic Vehicle Location:** Most AVL systems record a GPS timepoint, heading, average speed, and schedule adherence and then transmit data over a radio network. The transmission may occur every 90 to 120 seconds based on the radio system capacity. However, the resolution of the AVL data for these transmission rates is inadequate for isolating the effects of individual signals. In addition, the limited capacity and reliability of AVL data transmission is unacceptable for the purpose of measuring TSP performance, due to the low frequency of data points.
- **Automatic Passenger Counters:** An APC records the number of boardings and alightings, as well as GPS location/timestamps for each boarding/alighting. APCs are sometimes equipped with their own GPS units or use data from other equipment on the bus (e.g., AVL system). These devices may record position data every 2 to 20 seconds, making them a potential source of high resolution data. The utility of an APC can be limited due to the need to manually download data or also by the software required to access the data.

- **TSP GPS System:** GPS based priority request systems may log vehicle location, priority request status, speed, and heading on a second by second basis. Data can be stored onboard the bus or may be available at a city traffic management center. The high resolution of these data enables measurement of TSP effects on individual intersections, but depending on the configuration may not provide reliable route information.

These examples clearly demonstrate that the type of equipment available dictates which MOEs (Table 5.1) can be evaluated. The types of equipment discussed above lend themselves most readily to measuring travel time/speed, ridership, and TSP characteristics. Understanding the parts of these measures is essential to finding ways to measure them. Travel time is the result of two components -- movement time (while the bus is moving forward), and delay time (while the bus is waiting). TSP can affect both of these components, and vice versa, these two measures can help to determine the effects of TSP. Reliability is the combination of on-schedule performance as measured over a range of time scales, from hour to hour through the day, and from day to day through the year. Reliability is naturally customer focused -- it directly affects ridership. However, it can be quantified through data collection. TSP affects reliability in both long-term and short-term time scales, and thus the reliability of the system can yield data about the performance of TSP.

The accuracy of any measurement is highly dependent on how often data points are logged. Although it may be tempting to use a system already widely used (like AVL), determining TSP performance requires much more frequent data points. Second-by-second data are required because TSP impacts bus performance at the level of individual intersections; thus, the amount of time between data points must capture the changes in motion while the bus is within the vicinity of a single intersection. Figure 5-1 illustrates this point. As shown in Figure 5-1, the bus passes through four intersections between the data points at 8:27:01AM and 8:28:58AM. While it can be seen how long it took the bus to travel between those two points (and thus its average speed based on the distance between them), it is not evident whether the bus experienced delay at any of the intersections, or whether it picked up passengers.

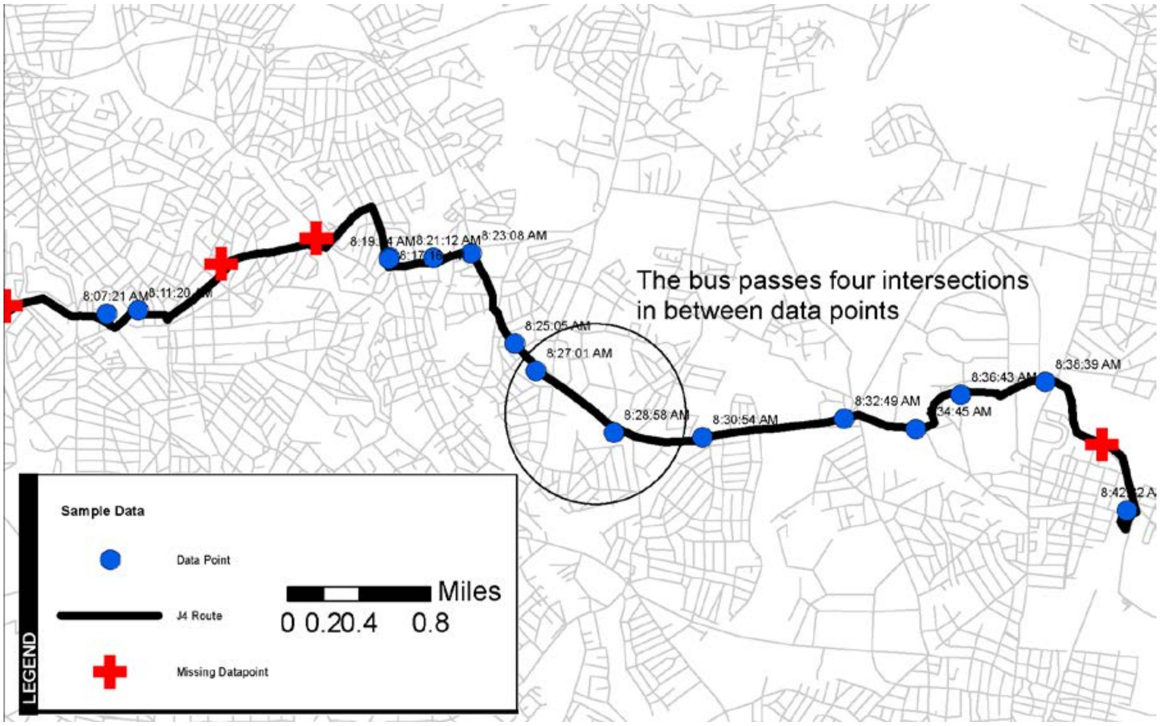

Figure 5-1: Measuring TSP Effectiveness with Low Resolution Data

Using higher resolution data, Figure 5-2, illustrates that a bus experiences 20 seconds of delay at the Beltsville traffic signal and seven seconds of delay at the Powder Mill traffic signal.

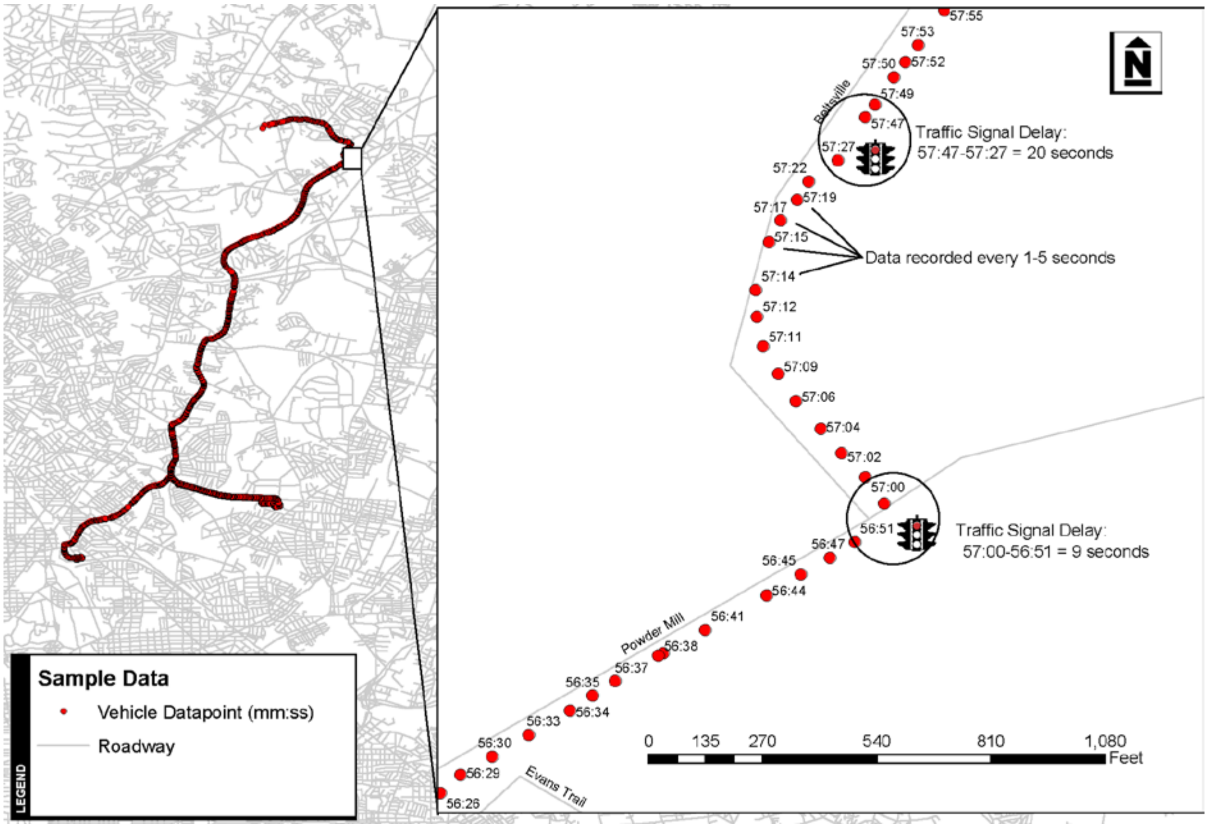

Figure 5-2: Measuring TSP Effectiveness with High Resolution Data

Transit signal priority can make transit systems more appealing, reduce fuel consumption, and streamline traffic operations in a variety of environments. As transportation demand grows, implementing systems such as TSP will become even more important to meet this demand. Planning future TSP systems depends heavily on understanding how TSP affects a system and this understanding can only be taken from measuring and evaluating existing systems. A variety of sources can provide data that are useful for measuring the effectiveness of TSP, but some sources are much more useful than others. How often data points are recorded, what information is recorded, and how that data are stored, accessed, and shared has significant impact on how well TSP performance can be measured. TSP should be measured to realize that maximum potential benefit. Further research in measuring TSP performance is needed.

5.3.2 Use of Detailed Traffic and Transit Operations Data for TSP Evaluation

This section provides an evaluation of TSP performance that represents an approach to data collection that is consistent with those described in this report. Evaluations were conducted along two existing corridors:

- Santa Clara Valley Transit Authority (*VTA TSP*) Line 22 Corridor
- San Mateo County Transit District (*SamTrans ATSP*) Route 390 Corridor

In addition, the queue jump operations at the intersection of El Camino Real and Arastradero Road (along the VTA TSP corridor) were also evaluated.

The data collection methodology is described for each corridor. An automated data collection system has been established to collect continuous time stamped data for transit operations and TSP requests, traffic signal operations, and traffic conditions in those corridors.

In each instance, an integrated transit, traffic operations database was developed. The database provides a coordinated instant by instant picture of events associated with the operation and performance of TSP. In addition to the evaluation in this study, the database is available for future research.

MOEs have been calculated for the transit vehicles and general traffic along the two corridors. Each MOE is compared before and after TSP implementation, with the intent to quantify the impacts on the various stakeholders.

Descriptions of the corridors and their data collection systems are provided below.

5.3.3 Data Collection System Configuration

The data collection systems for the VTA Line 22 Corridor and SamTrans Route 390 corridor are shown in Figure 5-3 and Figure 5-4, respectively.

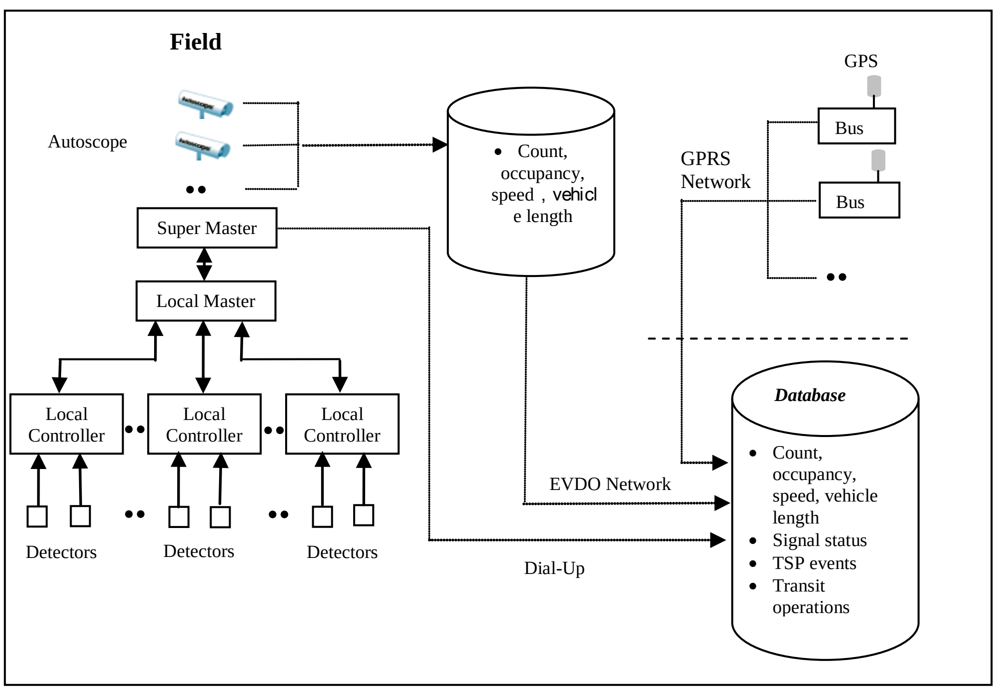

Figure 5-3: Data Collection System for VTA Line 22 Corridor

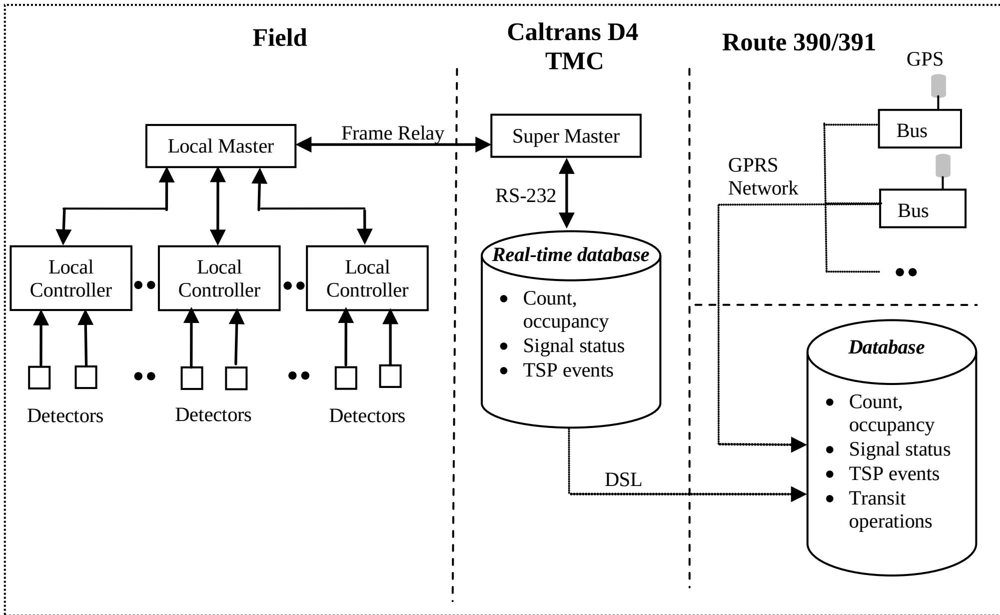

Figure 5-4: Data Collection System for SamTrans Route 390 Corridor

The data collection systems seem quite extensive, but the primary element that was added beyond the existing systems was the database system and the communication links that would populate the database. In both cases, the data were received from the traffic agency and the transit agency through a cooperative agreement to share the data.

Traffic signal status from local controllers and vehicle counts from loop detectors were collected at near real-time intervals (every two seconds in the VTA corridor and every second in the SamTrans corridor), and transit GPS-AVL data were recorded second by second.

As part of VTA Rapid 522 BRT deployment, one queue jump lane has been constructed on southbound El Camino Real at the Arastradero Road intersection. To quantify the queue jump operation, Autoscope cameras have been installed at this intersection to collect data on real-time signal indication, traffic volume, speed, and vehicle length.

Additional information about the TSP implementation sites for the VTA Line 22 and the SamTrans Route 390 corridor is provided in Appendix B and C, respectively.

5.3.4 Database Development

The information collected by each system is provided to a database. The database design is shown in Figure 5-5. Five types of data were collected from each of the sites. These include transit vehicle, traffic signal, loop detector, Autoscope, and TSP data. To facilitate automated data processing, all data were synchronized using Coordinated Universal Time (UTC). The database fields, definitions, and examples are provided in Table 5-3

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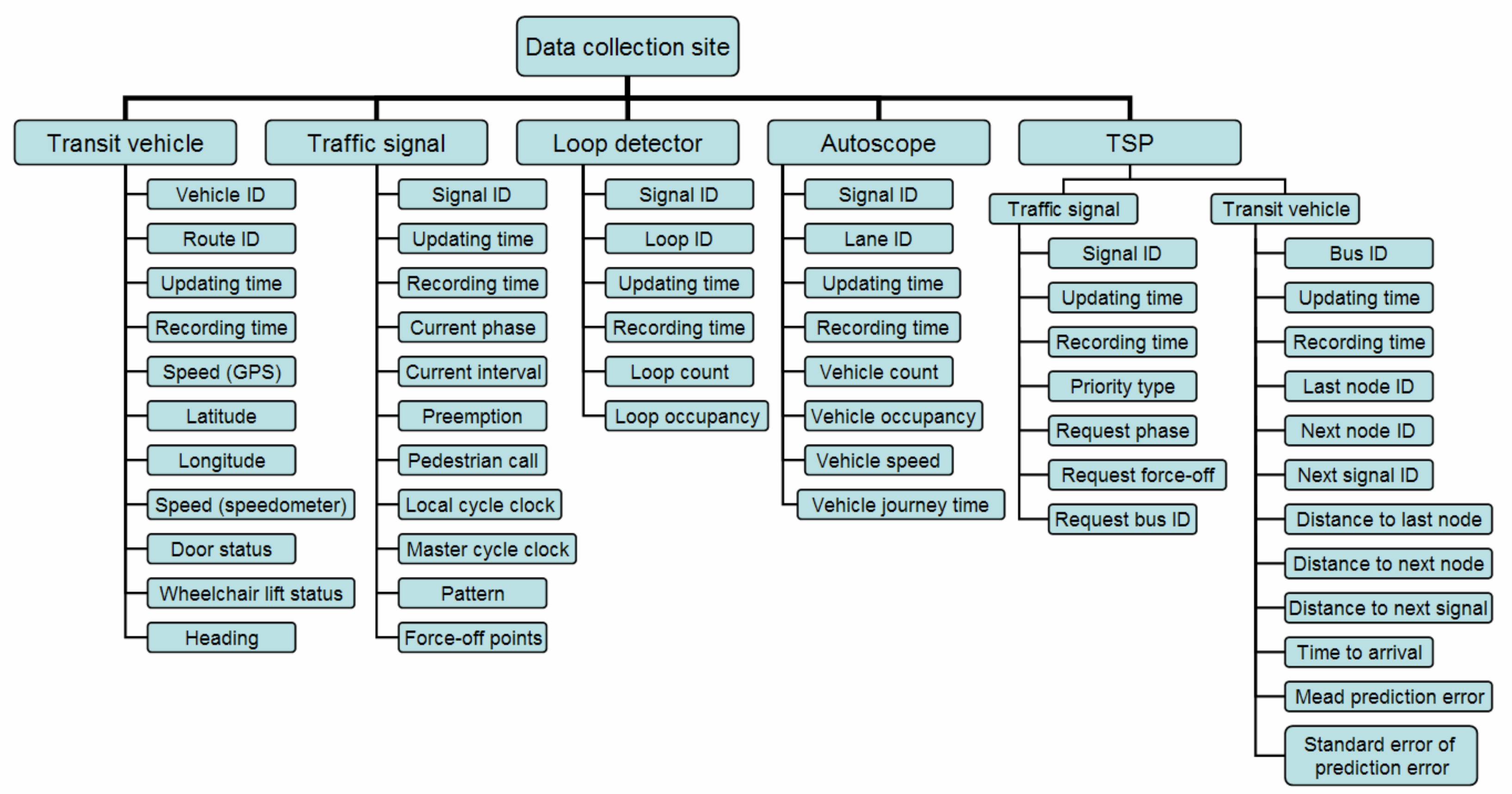

Figure 5-5: Overall Database Design

Table 5-3: Database Entry Definitions

Field	Type	Description	Example Entry
SiteID	Integer	Index for the data collection site	1
VehID	Integer	Index for the transit vehicle	1
RouteID	Integer	Index for the transit route	1
UpdateTime	String	Time of day this data was updated in hh:mm:ss.sss	11:11:11.111
RecordTime	String	Time of day this entry was recorded in hh:mm:ss.sss	11:11:11.111
Speed	Float	Vehicle speed (meter/second)	11.111
Latitude	Float	Latitude in degree and decimal minutes (ddmm.mmmmmm)	1111.111111
Longitude	Float	Longitude in degree and decimal minutes (ddmm.mmmmmm)	1111.111111
Door	Integer	Door open/close status (0 for close; 1 for open)	1
Wheelchair	Integer	Wheelchair lift status (0 for close; 1 for open)	1
Heading	Integer	Heading direction for transit vehicle	1
SignalID	Integer	Index for the signal	1
Faze	Integer	Current phase (8 bit binary 01000100)	34
Interval	Integer	Interval for current phase (8 bit binary 00010001)	136
Preemption	Integer	Preemption status (binary)	1
PedCall	Integer	Pedestrian call for all movements (00000001)	1
LocalClock	Integer	Local cycle clock (0~Cycle length-1)	1
MasterClock	Integer	Master cycle clock (0~Cycle length-1)	1
Pattern	Integer	Current pattern	1
FO	integer	Force-off point for each phase	20
LoopID	Integer	Index for the loop detector	1
LoopCount	Integer	Vehicle count from the loop detector	11
LoopOccu	Float	Occupancy from the loop detector	0.5
LaneID	Integer	Index for the lane (count from the right most lane)	1
AutoCount	Integer	Vehicle count from the Autoscope system	11
AutoOccu	Float	Occupancy from the Autoscope system	0.5
AutoSpeed	Float	Speed of the detected vehicle	11.111
AutoTT	Float	Travel time of the detected vehicle	11.111
PriorityType	Integer	Priority type (0 for no priority;1 for early green; 3 for green extension)	1
ReqFaze	Integer	Request timing changes on the phase	1
ReqFO	Integer	Request force-off point for the ReqFaze	15
ReqBus	Integer	Index of the bus requesting TSP	1
LastNode	Integer	Index of the last node which the bus just passed	10
NextNode	Integer	Index of the next node which the bus will arrive at	11
NextSignal	Integer	Index of the next signal which the bus will arrive at	11
DistLastNode	Float	Distance to the last node	90.999

Field	Type	Description	Example Entry
DistNextNode	Float	Distance to the next node	110.111
DistNextSig	Float	Distance to the next signal	110.111
TTA	Float	Time to arrive at the next signal	11.111
MeanErr	Float	Mean of the prediction error	5.555
SDErr	Float	Standard error of the prediction error	2.222

Routine database maintenance functions have been developed. These include: 1) data cleanup to monitor all files received and automatically delete duplicate information, 2) delete empty files function, and 3) a function that keeps a log file of all cleanup operations. Whenever the cleanup tool detects an abnormality, including the absence of an update, it notifies the administrator and record it in a log file.

5.3.5 Evaluation of Benefits of TSP to Transit Vehicles

This section provides a summary of the evaluation results. More detailed discussion can be found in Appendix E.

5.3.5.1 VTA TSP System

Trip-Based MOE

Trip-based MOEs include trip travel time (in terms of dwell time), total stopped time, number of stops at red, and number of stops at prioritized intersections. The results include the following

- TSP operations reduced bus trip travel time and total intersection stop time in all cases studied, in terms of traveling direction and time-of-day.
- In cases where the number of stops at red was reduced, the impacts were statistically significant (at 5% level of significance). Taking mid-day peak westbound bus tips as an example, bus travel time was reduced by 10% or two minutes, total intersection delay was reduced by 25% or one minute, and bus average traveling speed was increased by 4% or 1 MPH.
- In cases where the number of stops at red was increased, such as afternoon-peak eastbound bus trips, the impacts were statistically insignificant.

The results also show that the receipt of successful TSP execution at upstream intersections affects bus delays at the downstream intersections. Two examples are presented in Appendix E to demonstrate this finding.

Intersection-Based MOEs

There are two measures at the intersection: 1) frequency of stops, and 2) average stopped time. At the intersection level, TSP benefits include the following:

- At intersections where the average bus delay was greater than 30 percent of the length of the signal cycle, TSP operations reduced bus intersection delay by up to 43% or 16 seconds. The reduction was statistically significant at 5% level of significance

- At intersections where the average bus delay was in the range of 10 percent to 30 percent of the cycle length, TSP operations were likely to reduce bus intersection delay. The higher the delay was, the more likely the reductions were statistically significant (at 5% level of significance).
- At intersections where the average bus delay was less than 10 percent of the cycle length, the impacts on bus intersection delay were likely to be statistically insignificant. The changes in delay were generally within three seconds.

The detailed comparison results are shown in Appendix E.

Reliability/Schedule Adherence

Reliability and schedule adherence were evaluated using measures of the average and the maximum arrival deviation from schedule, the variance of the deviation at time-point, and the average and variance of travel time between time-points. The definition of on-time performance varies by operator. VTA defines a bus to be late if it is over five minutes behind schedule.

There are three time-points on Route 522 -- California Avenue, Showers Drive, and Castro Street. The distance between the three time points is 2.7 and 1.7 miles, respectively. The scheduled headway of Route 522 is 15 minutes.

A comparison of on-time performance for "before" and "after" TSP implementation shows the following:

- The bus on-time rate increased by 6% westbound and by 4% eastbound.
- The maximum arrival deviation decreased by one minute westbound and by three minutes eastbound.
- The average arrival deviation decreased by two minutes westbound and by one minute eastbound. The changes are statistically significant at a 5% level.
- The variance of arrival deviation increased by 30% westbound, as upon receiving priorities, a bus is likely to arrive earlier (ahead of schedule by more than one minute) at a bus stop. The change is statistically insignificant.
- The variance of arrival deviation decreased by 39% eastbound, as the evaluation site is very close to the starting point for eastbound trips and the bus is likely to be on schedule. The change is statistically significant at a 5% level.
- The average travel time deviation between the first and the last time-point (e.g., California Avenue and Castro Street) decreased by 41 seconds in both directions. The changes are statistically significant at a 5% level.
- The variance of travel time deviation decreased due to TSP operations. The changes are statistically insignificant.

5.3.5.2 SamTrans ATSP System

Trip-Based MOEs

The below observations were made based on the comparison of the bus trip MOEs for the "before" and "after" scenarios. For a detailed data analysis, refer to Appendix E.

- The operations of ATSP reduced bus trip travel time by 13%, or 51 seconds, northbound and by 9%, or 32 seconds, southbound. The changes are statistically significant.
- ATSP increased bus average traveling speed by 11% (1.5 m/s or 3.4 MPH) northbound and by 7% (1.1 m/s or 2.4 MPH) southbound. The changes are statistically significant.
- ATSP reduced total intersection delay by 19%, or 26 seconds, northbound and by 14%, or 18 seconds, southbound. The maximum intersection delay was reduced by 19%, or 11 seconds, northbound and by 18%, or 9 seconds, southbound. The average delay per stopped intersection was reduced by 14%, or 6 seconds, northbound and by 9%, or 3 seconds, southbound. The changes are statistically significant.
- ATSP operations reduced the number of stops at traffic signals. The changes are statistically insignificant because the objective of ATSP is to minimize the weighted bus and normal traffic delay rather than to minimize the number of stops.

Intersection-Based MOEs

In comparing the "inferred before" scenario to the "after scenario," average bus intersection delays were reduced at all intersections (by 95%, 53%, 43%, 60%, and 69% at 9th Ave., 17th Ave., 25th Ave., 27th Ave., and 28th Ave., respectively) and average passenger delays for all approaches including buses were reduced (by 55%, 14%, 12%, 35%, and 62% for the five intersections, respectively). Refer to Appendix E for a detailed analysis.

5.3.6 Evaluation of Impacts of TSP to Traffic

5.3.6.1 Methodology for the Calculation of Traffic Intersection Delay

Traffic delay at prioritized intersections is the major measure of TSP impacts to traffic. This section presents methods to calculate traffic delay based on loop measurements.

Figure 5-6 illustrates the concept of using cumulative plots of advance-loop and presence-loop counts to calculate the average traffic delay[21].

[21] C.F. Daganzo, Fundamentals of Transportation and Traffic Operations. Elsevier Science Ltd., 1997.

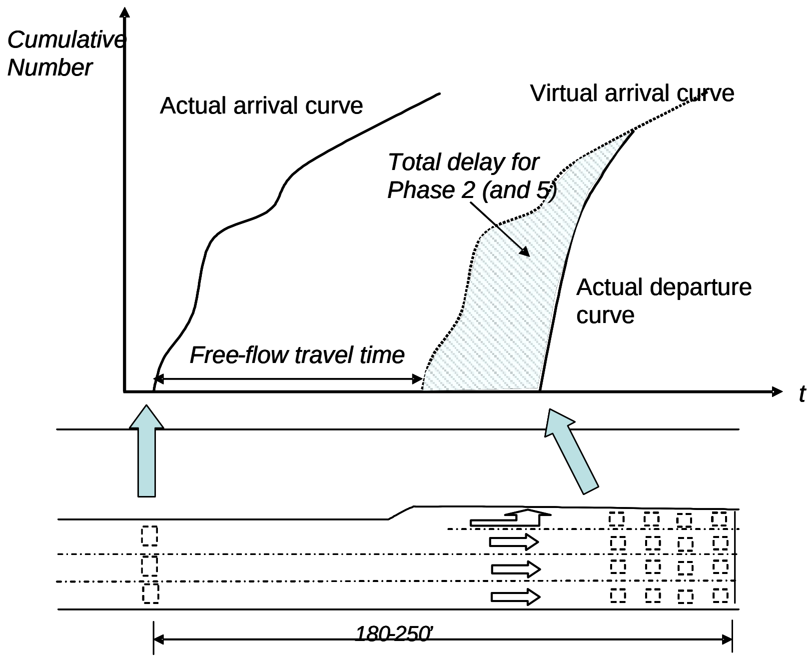

Figure 5-6: Delay Calculation Concept using Advance and Presence Loops Counts

The arrival / departure curves indicate the cumulative number of vehicles that have passed the advance / presence loops, respectively, by time, *t*. The virtual arrival curve is a translation to the right of the actual arrival curve by the amount of free-flow travel time between advance and presence loops. The virtual curve only represents the number of vehicles that would have been observed if the last vehicle in the queue was served. The area of the region between the virtual arrival curve and the departure curve is the total delay caused by the signal control. Average delay can be estimated using the following equation:

$$\bar{d} = \frac{T_d - T_a}{N} - \tau$$

where: $\bar{d}$ = the average delay (sec/veh)

T_a = the sum of absolute UTC times of arrivals (sec)

T_d = the sum of absolute UTC times of departures (sec)

N = total number of arrival/departure vehicles

τ = (average) free-flow travel time between advance and presence loops

Semi-actuated signals have advance loops for through movements and presence loops for left-turn and cross-street movements. Consequently, the delay calculations presented above cannot be applied directly.

To calculate the mainline through movement delay, the departure curve must be estimated. A maximum departure rate (the slope) of 1800 veh/lane/hr is assumed. Figure

5-7 illustrates the cumulative actual and virtual arrival curves, and the estimated departure curve.

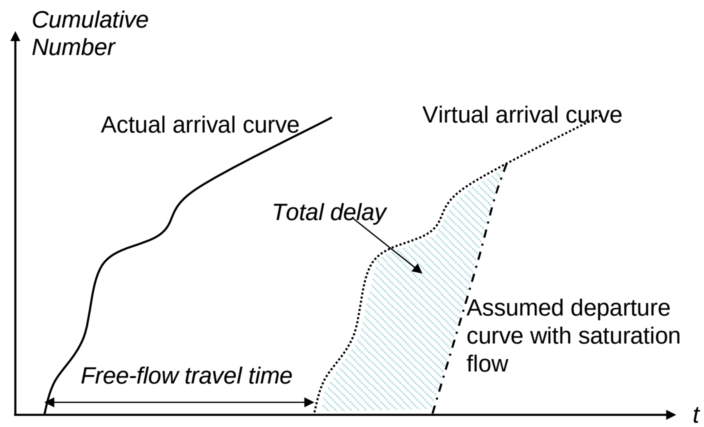

Figure 5-7: Delay Calculation Concept using only Advance Loops Counts

To calculate the mainline left-turn and cross street delay, the arrival curve must be estimated. The following two assumptions are made: 1) traffic arrivals are uniformly distributed (the slope is linear), and 2) the minor phases gap-out. Figure 5-8 illustrates the estimated arrival curve and the actual departure curve.

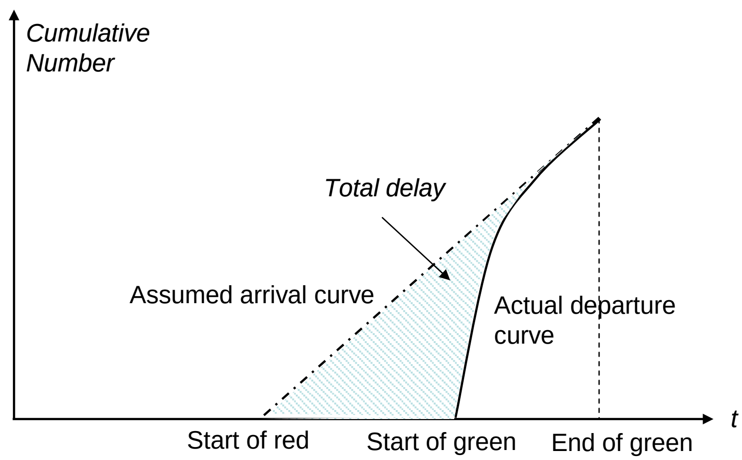

Figure 5-8: Delay Calculation Concept using only Presence Loop Counts

Although assumptions have been made to facilitate the delay calculation, these assumptions are often justifiable. The adopted approach provides reasonable estimates of signal delay, provided that loop detector data are accurate.

5.3.6.2 VTA TSP System

The average major and minor phase delays were estimated at five intersections in terms of time-of-day. The time-of-day peaks were selected using the traffic profile along the corridor, and are consistent with the signal timing patterns.

Appendix E presents the estimated average delay for the "before" and "after" TSP scenarios. The findings are the following:

- The impacts of TSP on both major and minor phase delays at uncongested intersections are statistically insignificant (e.g., Cambridge and Jordan whose saturation degrees are in the range of 0.3 to 0.4).
- At the medium congested intersections with degrees of saturation between 0.5 and 0.7, such as Charleston, San Antonio, and Page Mill, the impacts are both statistically significant and insignificant. The more congested an intersection is, the more likely the impacts are statistically significant.
- At intersection with significant impacts, TSP operations reduce the mainline traffic delay by 9% to 27%, and increase the minor-phase delay by 8%.

If one is only concerned about the net change in average delay before and after TSP implementation, the above cases may become insignificant. For example, if the frequency of TSP operation at Page Mill is less than eight and six times per hour in the midday and evening peaks, respectively, the minor phase delay would increase by 8% in the midday and the major-phase delay would decrease by 27% in the evening. The net change in average delays would be insignificant.

5.3.6.3 SamTrans ATSP System

The "after" scenario average major phase delay is reduced by 81%, 14%, 16%, 36%, and 74% at 9th Ave., 17th Ave., 25th Ave., 27th Ave., and 28th Ave., respectively, while the average per minor phase vehicle delay is increased by 0.93 seconds, 1.49 seconds, 1.39 seconds, 0.21 seconds, and 3.53 seconds for the five intersections, respectively. The reductions of major phase delay are statistically significant and the increases in minor phase delay are statistically insignificant at most intersections except 17th Ave. Refer to Appendix E for a more detailed analysis.

5.3.7 Evaluation of Queue Jump Lane Operations

Queue jump operation, which allows buses to bypass a waiting queue, has being widely deployed as part of BRT systems. However, the characteristics of queue jump operation have not been quantitatively studied, possibly due to the difficulty in obtaining queue jump operations data. The ability of some video detection units to detect vehicle length makes this a desirable system for collecting queue jump operations data, where buses can be automatically differentiated from general traffic via vehicle length characteristics.

The queue jump operations on southbound El Camino Real at the Arastradero Road intersection used the existing right-turn lane and a "receiving" lane across the intersection. The length of the right-turn pocket, measured from the stop-bar to the start of the on-street parking zone, is 193ft (59m) and the width of the intersection is 114.5ft (35m). There is no transit phase specifically designed for queue jump operation. In other words, the bus driver in the queue jump lane and the drivers in the adjacent through lane all receive the same signal indication and the bus must merge to its left before the end of the “receiving” lane.

Three weeks (15 weekdays) of data were collected using Autoscope video detection cameras and were analyzed. The findings are presented below.

5.3.7.1 Accuracy of Autoscope Measurement

The field of view of installed Autoscope cameras covers the queue jump lane (i.e., right-turn lane) and the adjacent through lane. The accuracy in measuring traffic volume using Autoscope sensors and conventional inductive loop detectors was quantified, using the absolute relative error as the measure of accuracy. For Autoscope, the mean absolute relative error was 7% for through traffic, 10% for right-turn traffic, and 8.5% overall. In contrast, the mean absolute relative error for inductive loop detectors is much higher, at 33%.

5.3.7.2 Queue Jump Lane Usage

Buses rarely use the queue jump lane. The reasons for this may include:

- **On-street parking blocks bus access to the queue jump lane** -- The length of the right-turn pocket is 195ft, which is roughly the same as the queue length of eight stopped vehicles. Taking the size of the bus into consideration, a bus can not get into the queue jump lane if there are more than seven vehicles queued ahead of it.
- **There is no transit phase for queue jump operation** -- Bus drivers might decide not to use the queue jump lane due to safety considerations (i.e., avoiding the merging operation after passing through the intersection).

5.3.7.3 Potential Bus Delay Saving if Using the Queue Jump Lane

Data from the Autoscope cameras contain vehicle speed, length, and the time-into-cycle when a vehicle is detected. This set of data allows the development of software to estimate queue length and determine the position of a bus in the queue. Therefore, the potential bus delay saving, if the bus used the queue jump lane, can be quantified.

Buses arriving at the intersection between 6 AM and 8 PM were picked as study samples. There were a total of 1,499 samples, an average of seven buses per hour. The bus stop rate at this intersection is 40%. In other words, buses crossed the intersection 60% of the time without stopping.

Figure 5-9 plots the empirical cumulative distribution function (CDF) of bus position in queue for the samples where a bus stopped for the red signal. Nineteen-percent of the time, the bus was the first vehicle in the queue, and 18% of the time there were more than seven stopped vehicles ahead of the bus.

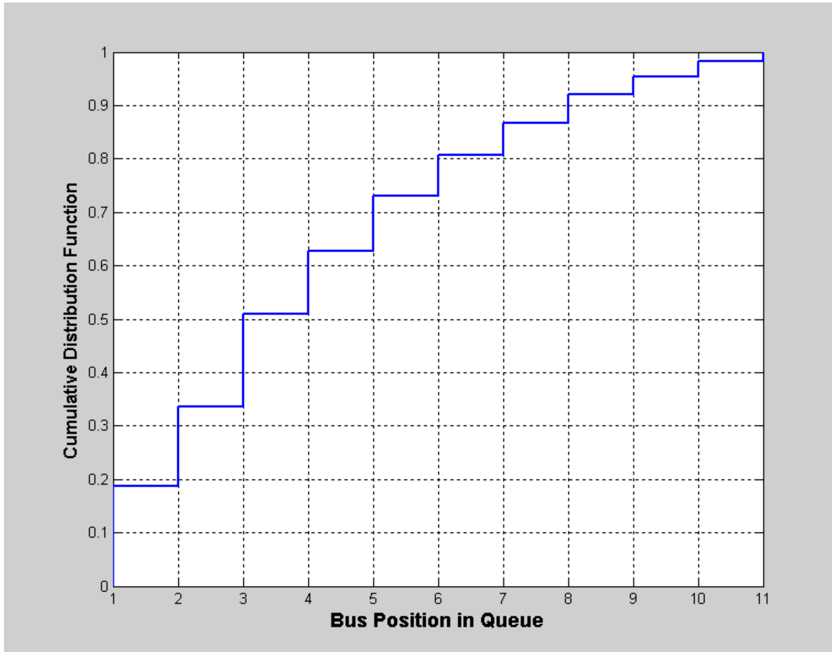

Figure 5-9 Empirical Cumulative Distribution Function of Bus Position in Queue

If there were vehicles stopped ahead of the bus, using the queue jump lane could reduce the intersection delay for the bus. Figure 5-10 shows the potential bus delay savings as a function of the bus position in queue. The overall average potential bus delay savings is 11 seconds, which equates to a 26% reduction in bus intersection delay as the average bus delay due to red is 42 seconds.

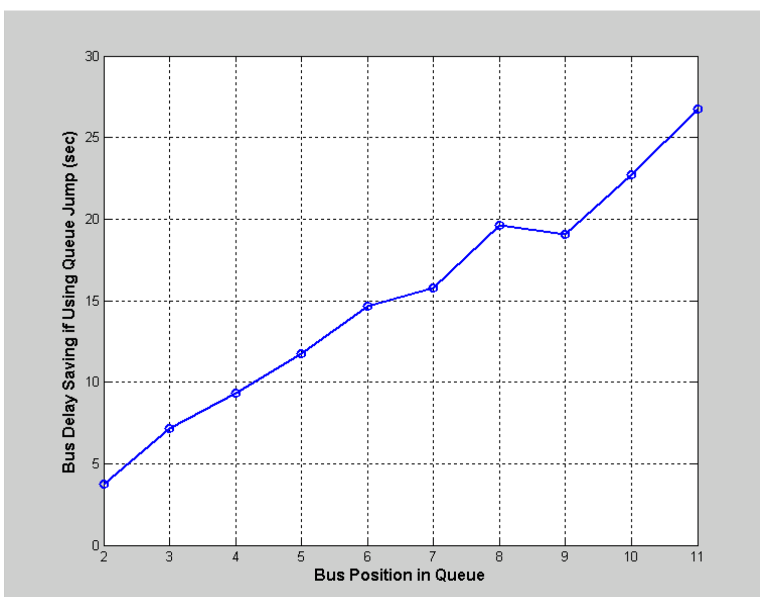

Figure 5-10 Potential Bus Delay Saving as Function of Position in Queue

In summary:

- The Autoscope video vehicle detection system produces better traffic measurement than conventional inductive loop detectors. The mean absolute relative error for Autoscope is 8.5% while that for loop detector is 33%.
- Buses rarely use the queue jump lane possibly due to two reasons: 1) on-street parking could block bus access to the queue jump lane, and 2) bus drivers might choose not to use the queue jump lane to avoid lane merging.
- If buses use the queue jump lane whenever it is needed, queue jump operation can reduce bus intersection delay an average of 11 seconds, or a 26% reduction.

For more effective queue jump lane design, the following two factors should be considered:

- Increasing the length of the right-turn pocket by moving the on-street parking zone farther upstream.
- Dynamically inserting a transit phase prior to the green on the through movement when a bus is detected in the queue jump lane.

5.4 TSP Performance Evaluation Summary

This chapter suggested a set of MOEs for evaluating the performance of a TSP system. The MOEs address reliability, travel speed/time, operating cost, pollutant emission, ridership, safety, and TSP performance for transit and arterial components. They could also be used to stratify the impact of the TSP system on different components of a transportation system, including transit vehicles, general traffic, and pedestrians. Having a common set of MOEs will help make the evaluation results comparable for different TSP implementations.

There are two types of approaches used to estimate the impact of a TSP project during planning stage – macroscopic and microscopic. Macroscopic ridership models are used to predict ridership changes with a TSP project, while macroscopic and microscopic traffic models estimate how traffic/transit operation condition would change in response to TSP implementation.

After a TSP project has been implemented, the evaluation of its impact should then be based on detailed (ideally second-by-second) traffic and transit operation data. This chapter presented evaluation process and results for two TSP projects using such data. The data from various sources (transit vehicle, other traffic, signal status) were synchronized using UTC and analyzed to evaluate the impact on the transit vehicles as well as general traffic. The MOEs used include both trip-based MOEs for transit vehicles, such as total trip time, total number of stops, total stop time, etc. and intersection-based MOEs, such as intersection delay for both transit vehicles and other traffic. From the evaluation process, it is also noted that the signal timing at downstream intersections will also affect the amount of transit vehicle travel time savings obtained from the priority treatment.

Appendix A: Implementation Background: LADOT Centralized TSP and LACMTA Decentralized TSP

The Metro Rapid Bus Program was initiated in March 1999 by LACMTA as a demonstration program. The initial phase of the Metro Rapid Bus was deployed on June 24, 2000, when the Metro Red Line subway was extended to the San Fernando Valley. The demonstration program aimed to offer rail-type frequent and high quality transit services connecting the terminus of the Red Line to major destinations in the outlining areas. Two lines were selected for the demonstration:

- Line 720 Wilshire/Whittier. This line is a very high passenger demand urban corridor connecting through the Los Angeles Central Business District;
- Line 750 Ventura. This line is a high passenger demand suburban corridor serving the Metro Rail Red Line.

The demonstration program has been a success, meeting all of its seven objectives:

- Reduce Passenger Travel Times
- Increase Ridership
- Attract New Riders
- Increase Service Reliability
- Improve Fleet and Facility Appearance
- Improve Service Effectiveness
- Build Positive Relations with Communities

Following the successful implementation of the Metro Rapid demonstration program, an expansion program identifying 26 additional corridors was developed. As of December 2005, a total of 15 corridors have been implemented. When completed in 2008, the Metro Rapid Program will operate a network of 450 miles of Metro Rapid service, complementing light and heavy rail transit throughout Los Angeles County.

The TSP system is a key attribute of the Metro Rapid Program. Two types of TSP systems have been implemented in the Rapid Bus Program. The first type uses the Transit TPS) software developed by LADOT, which requires a centralized control system and is used in 14 of the 15 corridors mentioned above; the other type is a decentralized system implemented along part of Crenshaw Boulevard (Figure A-1).

LADOT centralized system is implemented on 2070 type traffic controllers, while the decentralized system is used along a route where there are multiple jurisdictions and multiple types of controllers involved, which are listed in Table A-1.

Table A-1: Traffic Signal Controllers along Crenshaw Boulevard Corridor

Jurisdiction	Number of Intersections	Traffic Controller	Firmware
City of Los Angeles	10	2070	LADOT
City of Inglewood	14	170E	BiTran233
County of Los Angeles	7	2070, 170E	LADOT, LACO-4
City of El Segundo	2	2070	LADOT

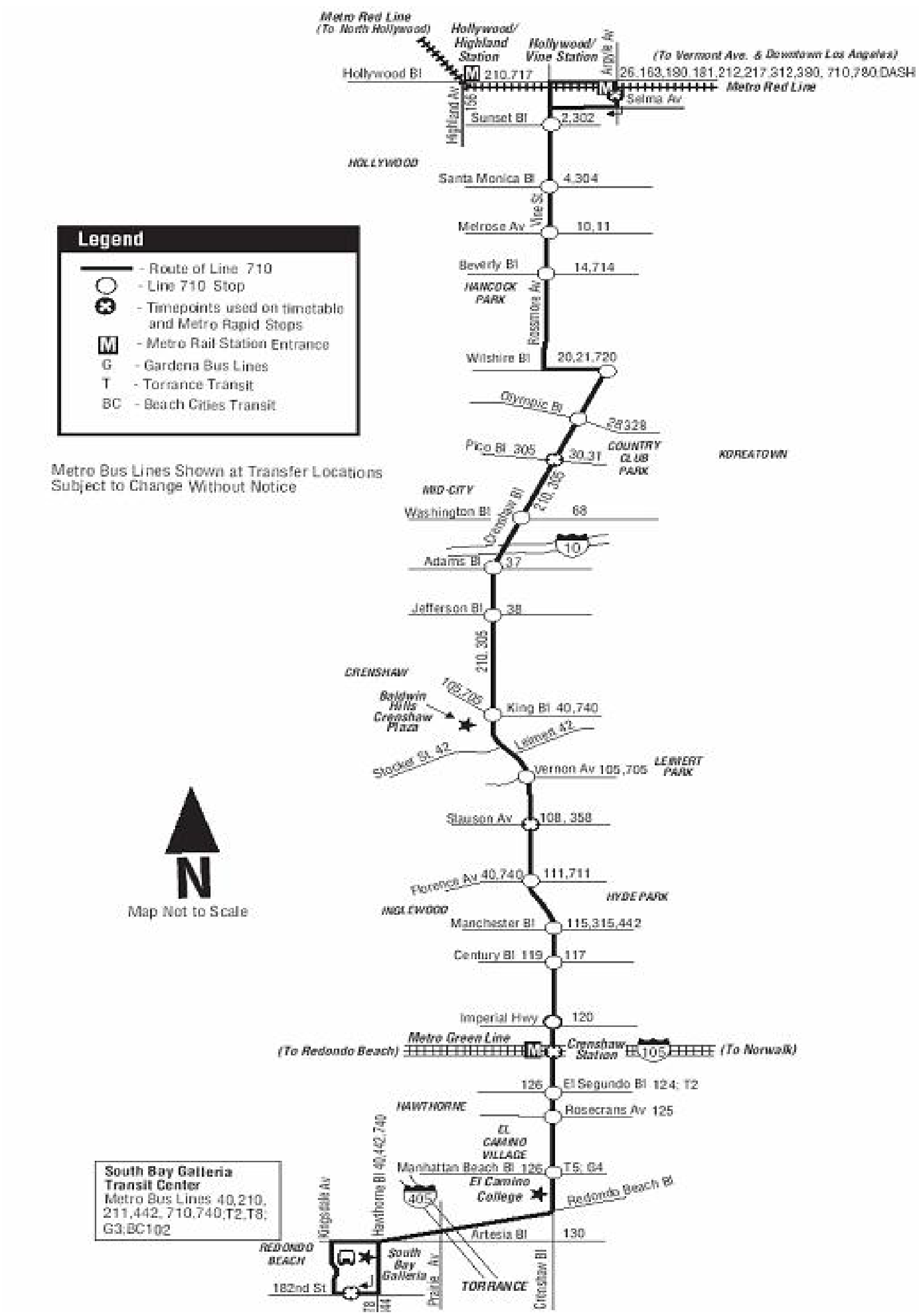

Figure A-1: Crenshaw Boulevard Corridor (Line 710) Source: http://www.metro.net/

Appendix B: Implementation Background: VTA Decentralized TSP

VTA and Caltrans have deployed BRT along a major arterial corridor, El Camino Real, in the Bay Area, where Line 22 and its express line, Rapid 522, are operated. The VTA TSP system was designed and installed by Caltrans Traffic Operations, Caltrans District 4 and VTA. The philosophy behind the design is to implement a cost-effective TSP based on existing discrete or decentralized traffic control systems with minimum modifications.

VTA Line 22[22]

Line 22 is the backbone of the VTA bus network. Line 22 provides service along the east-west length of the Santa Clara Valley between the transit center at Eastridge Shopping Center in San Jose, Santa Clara County and the Caltrain station in Menlo Park, San Mateo County. The corridor is twenty-seven miles long, as illustrated in Figure B-1. VTA Line 22 buses run every 10 minutes during weekdays, primarily along King Road, Santa Clara Street, The Alameda and El Camino Real (SR 82). Line 22 serves the cities of San Jose, Santa Clara, Sunnyvale, Mountain View, Los Altos, Palo Alto, and Menlo Park. It is VTA's most heavily used line, carrying over 23,000 riders daily and representing 16% of VTA's total bus ridership. The line operates near capacity, with many buses at standing room only.

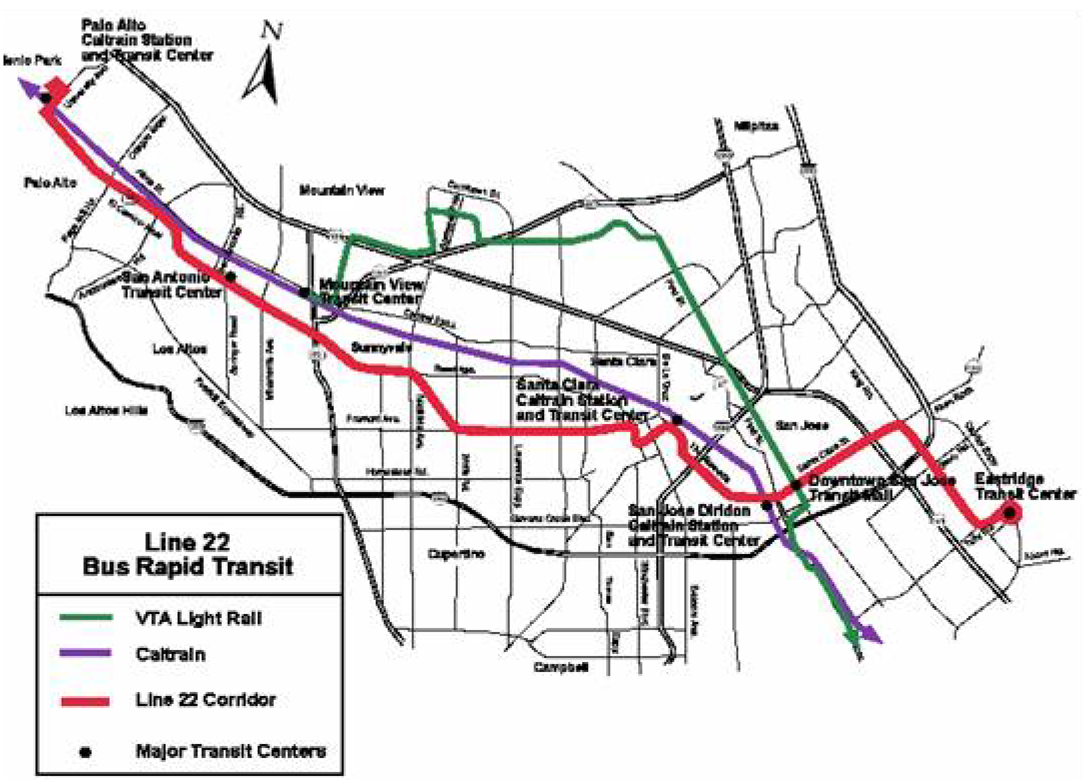

Figure B-1: VTA Line 22 Corridor (Source: VTA)

22 http://www.vta.org/projects/line22brt.html

VTA Rapid 522

Line 22 is supplemented by Line 300, a limited stop express service along generally the same corridor. Lines 22/300 connect with regional rail services as well as 55 VTA bus lines. A major connection occurs in downtown San Jose, where Line 22 intersects the north-south Guadalupe Light Rail Line. VTA’s vision for Line 22 is that it operates as a “BRT Corridor.” To achieve this vision, VTA has implemented VTA's Rapid 522 to replace Limited Stop Line 300 and supplement Line 22, providing faster, more frequent, and more direct service between Eastridge in San Jose and the Palo Alto Transit Center. The service frequency for Rapid 522 is 15 minutes on weekdays. The service combines state-of-the-art technology and service enhancements, including:

- Queue jump lanes at congested locations
- Advanced communication system
- Signal prioritization for buses to reduce delay
- Improved passenger facilities at stops
- High capacity, easy-access, and cleaner buses
- More frequent and direct service

Data Collection Sites

Figure B-2 and Table B-1 show the TSP intersection location where evaluation data are collected.

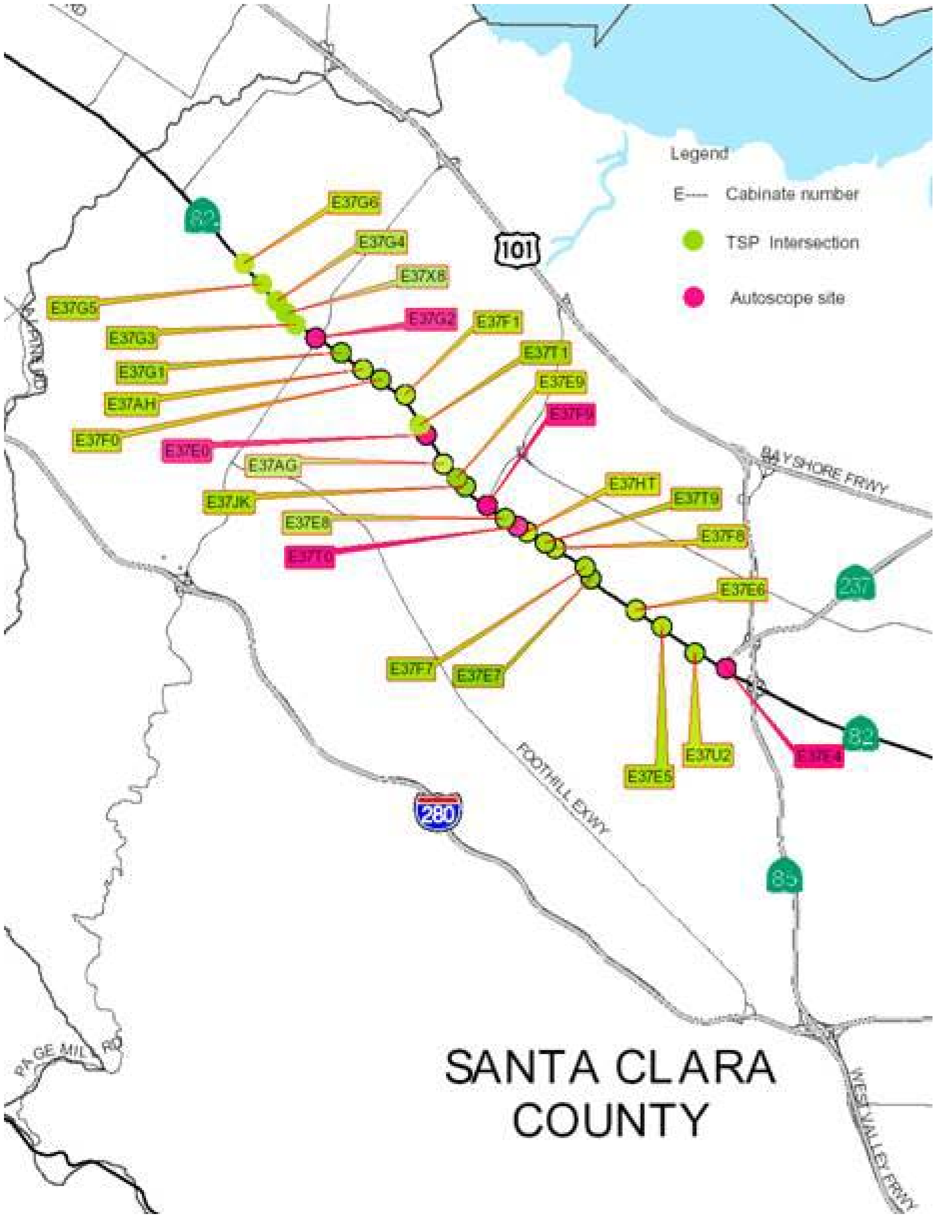

Figure B-2: Selected Intersections along VTA Line 22 TSP Implementation Site

Table B-1: VTA TSP Intersections (Cabinets & Cross Street)

Cabinet #	Cross Street	City	Recommended Autoscope Site
E37G6	Churchill Ave	Palo Alto	
E37G5	Park/Serra	Palo Alto	
E37G4	Stanford Ave	Palo Alto	
E37X8	Cambridge Ave	Palo Alto	
E37G3	California Ave	Palo Alto	
E37G2	Page Mill/Oregon	Palo Alto	•
E37G1	Hansen/Portage	Palo Alto	
E37AH	Matadero/Magarita	Palo Alto	
E37F0	Curtner Ave	Palo Alto	
E37F1	Los Robles	Palo Alto	
E37T1	Maybell	Palo Alto	
E37E0	Charleston	Palo Alto	•
E37AG	Dinahs CT	Palo Alto	
E37E9	Los Altos Ave	Los Altos	
E37JK	Del Medio	Los Altos	
E37F9	San Antonio Ave	Los Altos	•
E37E8	Shower Dr	Los Altos	
E37T0	Jordan Ave	Los Altos	•
E37HT	Ortega Ave	Los Altos	
E37T9	Distel Dr	Los Altos	
E37F8	South Rengstroff Ave	Mountain View	
E37F7	Escuela Ave	Mountain View	
E37E7	El Monte Ave	Mountain View	
E37E6	Shoreline Blvd	Mountain View	
E37E5	Castro St	Mountain View	
E37U2	Calderon Ave	Mountain View	
E37E4	Grant Rd/SR 237	Mountain View	•

Appendix C: Macroscopic Transit Ridership Forecasting Tools

C.1 Survey-Based Ridership Forecast

Some agencies use survey-based ridership prediction, which are based on simple non-committal surveys that ask potential riders how they would respond to new service or service changes. The response is then extrapolated for the total population and adjusted for non-committal bias. Surveys can also contain questions that segment riders into groups with similar characteristics. Extrapolation to the total population is conducted accordingly.

More sophisticated surveys borrow techniques such as conjoint analysis from marketing. Conjoint analysis tries to determine what combination of a limited number of attributes is most preferred by respondents through statistical methods. Surveyors show potential riders close substitutes which are dissimilar enough that respondents can clearly determine a preference. Conjoint analysis attempts to reveal true rider preferences instead of relying on the stated preferences of potential riders, often at the cost of longer questionnaire and smaller sample sizes. Both stated and revealed-preference surveys are prone to errors introduced by extrapolation and non-committal bias (even with adjustment, because the range of adjustment factors used in practice is large).

Although the implementation of TSP can be transparent to riders, the perception of TSP may influence rider attitudes toward transit. Marketing of the TSP program can make a difference in ridership. Therefore, it is very important for transit providers to understand how to appropriately interpret and utilize survey results.

C.2 Econometric Models of Transit Ridership

Factors affecting transit ridership fall in to two categories: exogenous (i.e. uncontrollable by or external to the transit agency) and endogenous (i.e. controllable or internal to the transit agency). Exogenous factors include population density, auto ownership rate, vehicle availability and ownership cost (such as fuel prices and parking availability). Other exogenous factors include the demographics of the community, topography, the extent of the transportation network, land use patterns, population and employment distributions. Endogenous factors include fare level, route structure (which affects walk time, ride time and transfer cost), service headway or frequency (which affects wait time), transit vehicle crowding (which affects comfort and safety), and service reliability.

The regression-based econometric models are sometimes referred to as “direct demand models”. Denote R the predicted ridership for a route, and X_i ($i=1,2,\ldots n$) the factors affecting ridership. Then the predicted ridership based on linear regression can be written as:

$$R = \lambda_0 + \sum_{i=1}^{n} \lambda_i X_i$$

For a discussion of relative importance of factors (both exogenous and endogenous) influencing transit ridership, readers are referred to Taylor and Fink (2002)[23].

In applying regression-based models, the level of analysis is of critical importance. Taylor and Miller (2003)[24] analyzed transit ridership in the urbanized area level. As such, the analysis was not capable to capture the impact of transit service level factors.

Notable recent route-level regression models include Stopher (1992)[25], Peng et al. (1997)[26] and Kimpel (2001)[27]. The latter specifically address transit service reliability and transit demand.

Walters and Cervero (2003)[28] analyzed ridership at individual transit station level, and included train frequency as a key predictor. A system called Transit Boarding Estimation and Simulation Tool (T-BEST)[29] is being developed for Florida DOT, to be used statewide for transit ridership forecasting. The core of T-BEST is a station-based regression model. Although the station-based models can potentially capture the impact of transit reliability, none have included this factor.

C.3 Elasticity-based Models of Transit Ridership

The predicted ridership based on elasticity can be written as:

$$R^a = R^b (1 + \sum_{i=1}^{n} e_i \frac{x_i^a - x_i^b}{x_i^b})$$

where b = the state before certain service change,

a = the state after the change, and,

e_i the elasticity of R with respect to X_i.

Elasticity-based models do not assume ridership to be the linear function of factors, however, they should be applied only when a small number of factors change, and the changes are small.

Numerous case studies have been conducted to estimate elasticity. For TSP, the elasticity of ridership with regard to travel time, wait time (or headway, frequency), and service

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23 B. Taylor and C. Fink, The factors influencing transit ridership: a review and analysis of ridership literature, UCLA Department of Urban Planning Working Paper, 2002

24 B. Taylor and D. Miller, Analyzing the determinants of transit ridership using a two-stage least squares regression on a national sample of urbanized areas, paper submitted for presentation at 2004 TRB Annual Meeting, July 2003

25 P. Stopher, Development of a Route-Level Patronage Forecasting Method, Transportation, Vol. 19, No. 3, 1992, pp. 201–220.

26 Z. Peng et al., A Simultaneous Route-Level Transit Patronage Model: Demand, Supply, and Inter-Route Relationship," Transportation, Vol. 24, No. 2, May 1997, pp. 159–181.

27 T. Kimpel, Time-point Level Analysis of Transit Service Reliability and passenger Demand, Ph.D. Dissertation, Portland State University, 2001

28 G. Walters and R. Cervero, Forecasting transit demand in a fast-growing corridor: the direct-ridership model approach. paper submitted for presentation at 2004 TRB annual meeting, August 2003

29 http://www.tbest.org

reliability are used to assess ridership changes. Martin and McGuckin (1998)[30] found that a variety of mode choice models produce reasonably consistent estimates of elasticity of transit ridership with regard to in-vehicle and out-of-vehicle travel times. The results are summarized in Table C-1 and Table C-2.

Table C-1: Elasticity of Transit Ridership with Regard to In-Vehicle Time

		Transit In-Vehicle Time (minutes)								
		20	25	30	35	40	45	50	55	60
Transit Probability	0.05	-0.48	-0.59	-0.71	-0.83	-0.95	-1.07	-1.19	-1.31	-1.43
	0.10	-0.45	-0.56	-0.68	-0.79	-0.90	-1.01	-1.13	-1.24	-1.35
	0.15	-0.43	-0.53	-0.64	-0.74	-0.85	-0.96	-1.06	-1.17	-1.28
	0.20	-0.40	-0.50	-0.60	-0.70	-0.80	-0.90	-1.00	-1.10	-1.20
	0.25	-0.38	-0.47	-0.56	-0.66	-0.75	-0.84	-0.94	-1.03	-1.13
	0.30	-0.35	-0.44	-0.53	-0.61	-0.70	-0.79	-0.88	-0.96	-1.05

Table C-2: Elasticity of Transit Ridership with Regard to Out-of-Vehicle Time

		Transit Out-of-Vehicle Time (minutes)								
		1.0	2.0	3.0	4.0	5.0	7.5	10.0	12.5	15.0
Transit Probability	0.05	-0.05	-0.10	-0.14	-0.19	-0.24	-0.36	-0.48	-0.59	-0.71
	0.10	-0.05	-0.09	-0.14	-0.18	-0.23	-0.34	-0.45	-0.56	-0.68
	0.15	-0.04	-0.09	-0.13	-0.17	-0.21	-0.32	-0.43	-0.53	-0.64
	0.20	-0.04	-0.08	-0.12	-0.16	-0.20	-0.30	-0.40	-0.50	-0.60
	0.25	-0.04	-0.08	-0.11	-0.15	-0.19	-0.28	-0.38	-0.47	-0.56
	0.30	-0.04	-0.07	-0.11	-0.14	-0.18	-0.26	-0.35	-0.44	-0.53

Evans (2004)[31] concluded that while available observations do not support a single numerical relationship between service frequency and patronage changes, the elasticity of ridership to frequency is on the order of 0.5, and most observations fall within the range from 0.3 to 1.0. In addition, "the effects on ridership of lack of reliability will be even more pronounced than the increase in waiting time alone indicates."

30 W. Martin and N. McGuckin, Travel Estimation Techniques for Urban Planning. NCHRP Report 365. National Research Council, Washington, D.C., 1998

31 J. Evans et al., Traveler Response to Transportation System Changes, Chapter 9, Transit Scheduling and Frequency, TCRP Report 95, Transportation Research Board, 2004

Pratt et al. (1981)[32] reported the effect of travel time reliability on transit ridership. The result is shown in Table C-3.

Table C-3: Effect of Travel Time Reliability on Transit Ridership

		New Standard Deviation of Headway (minutes)	
		4.0	2.0
Std. Dev. of Headway (minutes)	6.0	8%	14%
	4.0	----	6%

C.4 Four-Step Model for Demand Forecast and Impact Analysis

Metropolitan Planning Organizations (MPOs) often uses the traditional four-step model (i.e. trip generation, trip distribution, modal split, and traffic assignment) for transit ridership forecasting and impact analysis. For example, the Georgia Regional Transportation Authority (2003)[33] developed a sketch planning tool for evaluating ridership impact of various transit improvements. The mandated ridership forecasts under FTA's New Starts program are mostly conducted using the four-step model. Demand forecasting programs utilizing the four-step model include: EMME/2, TRANSCAD, VISUM, CUBE, TP+, TRANPLAN, and others.

Recently the FTA sponsored the development of the ITS Deployment Analysis System (IDAS), a sketch planning tool that evaluates the impacts of transit ITS improvements. Section A.1.4 of the IDAS User's Manual[34] specifically addresses TSP as follows:

1. Travel Time and Throughput
2. Run trip assignment for the control alternative.
3. Apply speed increases of 13 percent for all priority links identified by the user.
4. Run trip assignment for the ITS option.
5. Calculate the ratio of the ITS option travel time over the control alternative travel time (ITS option travel time/control travel time) for each O-D pair.
6. Apply this ratio to the control alternative bus transit in-vehicle time matrix to derive the ITS option bus transit in-vehicle time matrix.

32 R. Pratt, and J. Coople, Traveler Response to Transportation System Changes, 2nd ed., Federal Highway Administration, Washington, D.C., 1981.

33 Georgia Regional Transportation Authority, "RTAP Planning Process", in Regional Transit Action Plan, Atlanta, June 2003

34 Cambridge Systematics, Inc. IDAS –User's Manual, Appendix A

7. Run mode choice for the ITS option using the new bus transit in-vehicle travel time matrix, keeping the auto in-vehicle times constant between the control alternative and the ITS option. IDAS does not need to consider auto times in mode choice, because these are assumed to not change in any appreciable amount between the control alternative and the ITS option.
8. Run a final assignment for the control alternative and the ITS option with the new auto vehicle trips that consider the new mode choice shares.

The default link-speed increase of 13% for all priority links can be modified by the user. The manual noted that "the ranges of observed benefits of reduced travel times range from 1.4 percent to 42 percent (Ann Arbor, Atlanta, Australia, Chicago, China, Dallas, DeKalb County (GA), England, France, Italy, Japan, Los Angeles, Minneapolis, Oakland/Berkeley (CA), Portland, Seattle, Washington D.C.)."

The impact of TSP on safety, environment, energy, and noise can be calculated by IDAS based on changes in VMT, speed, cold starts, vehicle types, and facility type.

However, the IDAS tool fails to incorporate the impact of transit reliability improvement resulting from TSP. There are two reasons for this shortcoming. The impact of TSP is typically incorporated in the last two steps (modal split and traffic assignment) of four-step modeling process. For the modal split step, there are simply no consistent estimates of reliability's impact on transit ridership that are based on robust empirical evidence. For the traffic assignment step, most assignments are based on travel time comparisons and reliability impacts are not considered.

Because of reasons stated above, programs based on the four-step model are currently not capable of predicting the ridership impact of TSP if a TSP implementation significantly improves transit reliability.

C.5 Professional Judgment

Many transit agencies rely on professional judgment to predict ridership changes. Such professional judgment is based on experience and local knowledge. Sometimes this is due to the lack of data or expertise to support the development and use of formal models. Some may even argue that this reflects the lack of faith in formal models.

While there is little evidence of their accuracy or consistency, professional judgments are valuable when there are significant shortcomings in formal models. Our analysis suggests that may apply in the case of predicting the ridership impact of TSP. Professional judgments based on rules of thumb developed based on experience, combined with the "similar routes" approach, sometimes can be as good as any model output because critical elements missing from formal models may be captured.

Appendix D: TSP Representation in NGSIM

D.1 Transit Behavior Modeling in Microsimulation and NGSIM

For micro-simulators to accurately predict results of TSP strategies, and to evaluate the impact of TSP on transit vehicle as well as on other traffic elements, many other representations are required besides traffic signal timings. Transit network (including stops and terminals), transit vehicle types, routes and schedules need to be represented. To enhance stakeholders' confidence in simulation results, the simulation package needs to account for the behavior of transit vehicles, as well as the interaction between transit vehicles and other vehicles.

D.2 Overview of NGSIM

Starting in the 1970s, the Federal Highway Administration (FHWA) has established itself as a leader in the area of traffic simulation model development and has developed the widely used CORSIM model. When FHWA undertook this leadership role there were no commercial traffic simulation packages in the market. Now the market includes a number of viable traffic simulation packages such as AIMSUN, Paramics, and VISSIM. While FHWA continues to develop, maintain, and support the CORSIM model that is now integrated into the Traffic Software Integrated System (TSIS) package, it decided to examine its future role in traffic simulation and traffic analysis tools. CORSIM was never designed to model some advanced applications and it is difficult to maintain software written and engineered over twenty years ago. As a result, the focus of FHWA shifted to the Next Generation Simulation (NGSIM) program. NGSIM aims to develop a core of open behavioral algorithms with supporting documentation and validation data sets that describe the movement and interaction of multi-modal travelers and vehicles on the roadway system and their interactions with traffic control devices, delineation, congestion and other features of the dynamic traffic environment. The products of the NGSIM program will be openly distributed and made freely available to the broad transportation community.

NGSIM's priorities for algorithm development, in order of descending importance, are as follows:

- Developing tactical route execution algorithms to make a big impact by addressing clear gaps in modeling.
- Improving operational driving algorithms (car-following and gap acceptance) by considering a broader range of influencing factors that have not been well-characterized to date or have been missing completely in the influences considered in each algorithm category.
- Advancing strategic, en-route route modification behavioral algorithms that attempt to reflect the driver's response to information and traffic conditions.

Algorithms are currently being developed for the following:

- lane selection
- cooperative/forced freeway merging

- over-saturated freeway flow

NGSIM's vision for near-future algorithmic development includes the following:

- Effect of heavy vehicles, weather, work-zones, 2-way left-turn lanes on driver behavior
- Unsafe driving maneuvers
- Start-up lost time and queuing at signalized intersections
- Cooperative gap acceptance on arterials

D.3 TSP and Transit Representation in NGSIM

The NGSIM team conducted a core algorithm assessment to develop a view of the state-of-the-art of core algorithms and to review the state-of-practice of how and where influencing factors are implemented in the most widely-used simulation systems.

In the project report[35] for NGSIM Task E.1-1, it is recognized that the recent popularity of TSP has placed enormous interest in modeling transit in micro-simulation systems. Such modeling requires the following:

- Vehicle types and vehicle classes/categories that are representative of transit vehicles
- Ability to represent bus stops in the network
- Ability to represent bus routes in the traffic network
- Ability to represent bus schedules for each bus route
- Provision of bus dwell times for each bus route at each bus stop. Dwell times can either be distributions or a factor of the boarding and alighting distributions of passengers
- Capability of obtaining bus travel times from the system for calibration and validation of the travel times to real world travel times
- According to VISSIM's marketing brochure, "VISSIM models transit routes, various transit vehicle types, schedules, stops, stop types and dwell types." It is thus expected that the above requirements are being met by major micro-simulation packages.
- Although TSP affects traffic control, it is found that traffic control devices and their control logic are represented in all simulation models. The type of logic (pre-timed, actuated, and coordinated) does not affect driver behavior in all models.

The behavior models associated with transit are identified as follows:

- Dwell time distributions based on passenger boarding and alighting behavior

35 Next Generation Simulation (NGSIM) Core Algorithms Assessment, FHWA Technical Report (No. FHWA-HOP-06-009), July 2004

- Transit driving behavior – cars following buses and buses following cars are both different from normal car following
- Lane changing and entering/exiting pull-out areas

Unfortunately, because of lack of empirical research results, simulation packages currently on the market do not provide adequate behavior models associated with transit. There is an apparent need for transit behavior modeling in NGSIM.

D.4 Strategies to Promote Transit Behavior Modeling in NGSIM

The NGSIM program provides an opportunity to incorporate TSP in traffic simulation models. If successful, it will enable traffic engineers to evaluate the potential impacts of proposed TSP implementations. This, in turn, will promote TSP deployment where beneficial.

In addition to placing transit and TSP experts and advocates in NGSIM advisory board and stakeholder groups, promotion of transit behavior modeling and TSP representation in NGSIM can be done on three fronts: scenarios, algorithms, and influencing factors.

D.4.1 Transit-related Scenarios

NGSIM working groups developed 35 scenarios and ranked them according to four criteria:

- Importance: importance of the model
- Gaps: whether existing models are able to represent the event
- Success: probability that a successful model could be created
- Data: availability of relevant data

As illustrated in Table D-1, there are two NGSIM scenarios that are most relevant to transit - heavy vehicles and transit operations on traffic networks. The heavy vehicles scenario has been included in the planned research for the next three years. However, the scenario of transit operations has not because of its relatively low ranking, although it is deemed important. The reasons are that surveys in the early stage of NGSIM prioritization process suggested that existing models were doing a good job of handling this scenario and data quality were not good.

Table D-1: Transit-Related NGSIM Scenarios

Scenario Name	Importance	Gaps	Success	Data	Weighted Sum	Rank
Weight	0.3	0.25	0.3	0.15	1.00	
Truck models (heavy vehicles)	5.5	5	9.5	6.5	6.725	8
Transit operations on traffic network	8	4	6.5	6.5	6.325	15

It is a misconception that existing models are good enough to model the scenario of transit operations. In the core algorithm assessment conducted later, it has been noted that the overall level of detail of mixed-mode traffic models are much less sophisticated than models for homogeneous vehicular traffic. While most simulation systems consider vehicle characteristics and distinguish vehicle types, their vehicle types and characteristics are not taken into account when vehicles interact with each other. For example, bus drivers who are required to make stops would change lanes differently than other vehicles. The drivers of other vehicles would be more likely to change lanes when they follow a bus in service to avoid being forced to stop. For this effort, PATH will document such deficiencies of existing models to establish that this sophistication gap is still large.

The chance of success and availability and quality of data are highly correlated. Thus improving the availability of quality data is important. One example of such effort is that the California PATH Traffic Lab is currently collecting data on a few TSP corridors. The data coming from loop detectors, onboard AVL systems, and video detection systems, can be used to study the interaction of buses and other vehicles on signalized arterials. The interactions of buses and other vehicles on freeways can be studied from data acquired by the Berkeley Highway Lab on I-80 under free-flow and congested conditions.

D.4.2 Influencing Factors

Because scenarios are collections of influencing factors, the lack of understanding of transit and TSP-related influencing factors directly results in an under-representation in NGSIM scenarios. Influencing factors fall into five categories: traveler, vehicle, network, environment, and system management. Although signals, signalized intersections, physical dimensions are among the top 10 influencing factors, and they are greatly affected by transit and TSP, only a few influencing factors related to transit including vehicle characteristics have been identified by NGSIM. However, many more transit and TSP-related factors that affect traveler behaviors went unrecognized. Examples of unrecognized factors are:

- It is reasonable to expect differences in transit vehicle drivers and car drivers because of the differences in their responsibilities and training;
- Queue jumper lanes are sometimes used for TSP implementations;
- Different types of TSP implementation (e.g. driver-requested vs. automated) may lead to different behaviors of transit vehicle drivers.

Effort should be expended in further identifying transit and TSP-related influencing factors and establishing their importance in the top scenarios currently being investigated.

D.4.3 Transit Algorithms

Two key issues from the behavioral aspect of transit are of interest in the scope of NGSIM:

- Accurate representation of transit behavior at stops (boarding and alighting)
- Modeling of behavioral algorithms (car-following, lane-changing, gap acceptance, etc.) specifically modified for transit vehicles (i.e., drivers of transit vehicles)

Figure D-1 and Figure D-2, reproduced from the NGSIM Task E.1-1 report, show that the availability of research, documentation, and validation of transit behavior is poor.

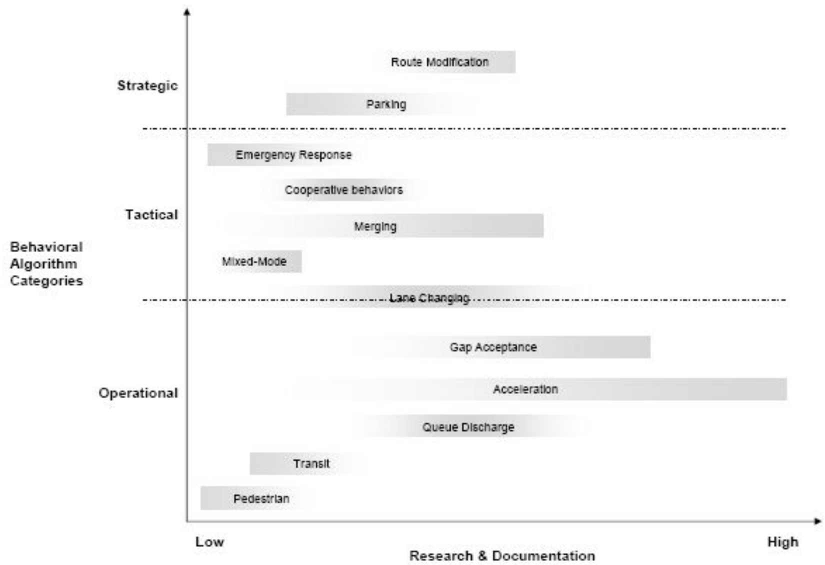


Figure D-1: Extent of Research & Documentation

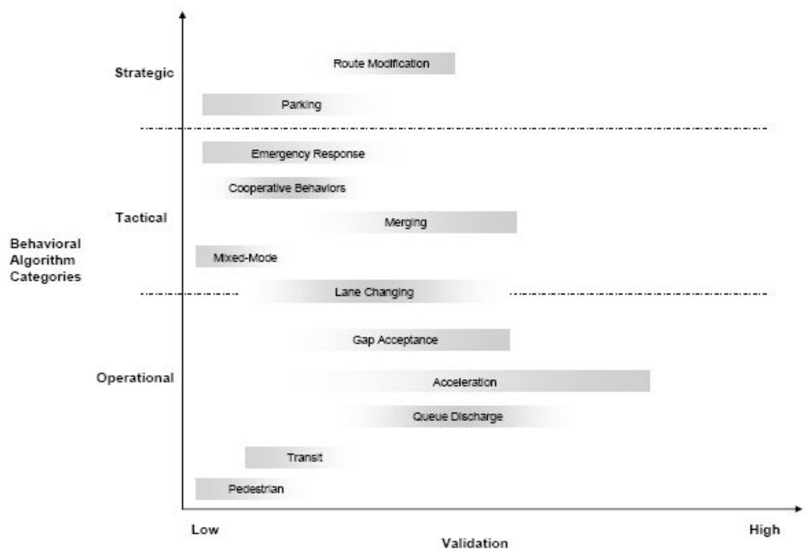


Figure D-2: Extent of Validation

Again, data collected by the PATH Traffic Lab and the Berkeley Highway Lab can be tailored to document transit behavior. They are useful for researchers to model and validate transit behavior at transit stops. The data currently being gathered can support efforts to document and validate gaps in transit algorithm development.

Appendix E: Detailed Evaluation of Existing TSP Systems

E.1 Evaluation of Benefits of TSP to Transit Vehicles

E.1.1 VTA TSP System

E.1.1.1 Reliability/Schedule Adherence

Table E-1 below illustrates the comparison of on-time performance for "before" and "after" TSP implementation. T-test and F-test were applied to test the significance of the change in sample mean and variation, respectively.

Table E-1: Comparison of Bus On-Time Performance

		California Ave		Showers Dr		Castro St	
		WB	EB	WB	EB	WB	EB
On-time rate (%)	Before	87.10	97.06	87.10	96.08	83.87	94.12
	After	92.19	99.12	87.50	99.12	85.94	98.21
	Change (%)	5.84	2.12	0.46	3.16	2.46	4.35
Maximum arrival deviation (min)	Before	7.53	5.91	7.46	8.15	7.88	9.65
	After	6.37	5.55	7.40	5.70	7.98	6.40
	Change	-1.16	-0.36	-0.06	-2.45	0.10	-3.25
Average arrival deviation (min)	Before	-0.39	0.26	-0.20	-0.02	0.41	0.99
	After	-2.03	0.32	-1.11	-0.27	-0.56	0.36
	Change	-1.65*	0.06	-0.90	-0.25	-0.97	-0.62*
	T-test	0.0205*	0.3907	0.1230	0.1999	0.0979	0.0299*
Variance of arrival deviation	Before	17.51	2.62	17.68	5.25	16.08	7.20
	After	22.68	2.18	20.13	4.06	19.13	4.40
	Change (ratio)	1.30	0.83	1.14	0.77	1.19	0.61*
	F-test	0.3122	0.3492	0.6115	0.1848	0.4980	0.0110*

* Significant at 5% level of significance

Table E-2 below illustrates the deviation in travel time between time-points for the "before" and "after" scenarios.

Table E-2: Comparison of Travel Time Deviation between Time-Points

		California← →Showers		Showers← →Castro		California← →Castro	
		Westbound	Eastbound	Westbound	Eastbound	Westbound	Eastbound
Average deviation (min)	Before	-0.18	-0.29	-0.61	1.01	-0.79	0.73
	After	-0.93	-0.59	-0.54	0.64	-1.47	0.04
	Change	-0.75*	-0.30*	0.07	-0.37*	-0.68*	-0.68*
	T-test	0.0006*	0.0384*	0.2652	0.0365*	0.0035*	0.0021*
Variation of deviation	Before	1.68	1.84	0.40	2.65	1.93	3.51
	After	1.54	1.36	0.36	2.01	1.91	2.45
	Change	0.92	0.74	0.91	0.76	0.99	0.70
	T-test	0.7362	0.1221	0.7218	0.1514	0.9749	0.0621

* Significant at 5% level of significance

E.1.1.2 Bus Intersection Stop Rate and Intersection Delay

Table E-3 below compares the intersection stop rates for the 21 TSP capable intersections on the evaluation route. Stop rate varies from intersection to intersection, and from peak to peak.

Table E-3: Comparison of Intersection Stop Rate

INT ID	Cross St	Direction	Intersection Stop Rate								
			Before (%)			After (%)			Change (%)		
			AM	MD	PM	AM	MD	PM	AM	MD	PM
2	Serra St	Westbound	0.0	0.0	0.0	5.1	0.0	7.1	5.1	0.0	7.1
		Eastbound	22.0	1.8	7.1	43.9	0.0	58.7	21.9	-1.8	51.6
4	Cambridge Ave	Westbound	34.4	46.9	50.0	41.0	45.5	21.4	6.6	-1.4	-28.6
		Eastbound	6.0	5.3	3.6	10.5	8.5	19.6	4.5	3.2	16.0
6	Page Mill Rd	Westbound	78.1	46.9	50.0	66.7	33.3	35.7	-11.4	-13.6	-14.3
		Eastbound	68.0	79.0	96.4	70.2	67.8	91.3	2.2	-11.2	-5.1
10	Curtner Ave	Westbound	9.4	15.7	0.0	2.6	12.1	7.1	-6.8	-3.6	7.1
		Eastbound	2.0	5.3	7.1	1.8	6.8	4.4	-0.2	1.5	-2.7
11	Los Robles Ave	Westbound	40.6	25.0	50.0	41.0	36.4	35.7	0.4	11.4	-14.3
		Eastbound	16.0	5.3	39.3	22.8	3.4	41.3	6.8	-1.9	2.0
12	Maybell Ave	Westbound	50.0	40.6	50.0	35.9	42.4	35.7	-14.1	1.8	-14.3
		Eastbound	20.0	33.3	28.6	15.8	17.0	34.8	-4.2	-16.3	6.2
13	Charleston Rd	Westbound	21.9	21.9	0.0	30.8	21.2	7.1	8.9	-0.7	7.1
		Eastbound	24.0	49.1	25.0	21.1	47.5	26.1	-2.9	-1.6	1.1

INT ID	Cross St	Direction	Intersection Stop Rate								
			Before (%)			After (%)			Change (%)		
			AM	MD	PM	AM	MD	PM	AM	MD	PM
14	Dinah's Court	Westbound	6.3	3.1	11.1	0.0	0.0	0.0	-6.3	-3.1	-11.1
		Eastbound	16.0	10.5	21.4	8.8	6.8	23.9	-7.2	-3.7	2.5
15	Los Altos Ave	Westbound	3.1	3.1	5.6	0.0	3.0	0.0	-3.1	-0.1	-5.6
		Eastbound	8.0	5.3	32.1	8.8	6.8	43.5	0.8	1.5	11.4
16	Del Medio Ave	Westbound	0.0	0.0	5.6	2.6	9.1	0.0	2.6	9.1	-5.6
		Eastbound	20.0	7.0	3.6	12.3	3.4	8.7	-7.7	-3.6	5.1
17	San Antonio Rd	Westbound	68.8	96.9	61.1	64.1	72.7	42.9	-4.7	-24.2	-18.2
		Eastbound	28.0	26.3	35.7	19.3	28.8	37.0	-8.7	2.5	1.3
18	Showers Dr	Westbound	6.3	15.6	11.1	15.4	12.1	0.0	9.1	-3.5	-11.1
		Eastbound	2.0	0.0	0.0	0.0	0.0	0.0	-2.0	0.0	0.0
19	Jordan Ave	Westbound	3.1	12.5	5.6	5.1	6.1	0.0	2.0	-6.4	-5.6
		Eastbound	12.0	21.1	25.0	7.0	20.3	21.7	-5.0	-0.8	-3.3
20	Ortega Ave	Westbound	0.0	3.1	0.0	0.0	3.0	0.0	0.0	-0.1	0.0
		Eastbound	18.0	42.1	7.1	8.8	20.3	4.4	-9.2	-21.8	-2.7
21	Distel Dr	Westbound	0.0	0.0	0.0	0.0	0.0	7.1	0.0	0.0	7.1
		Eastbound	2.0	12.3	14.3	12.3	13.6	6.5	10.3	1.3	-7.8
22	Rengstroff Ave	Westbound	6.3	6.3	0.0	2.6	0.0	7.1	-3.7	-6.3	7.1
		Eastbound	30.0	1.8	28.6	38.6	6.8	41.3	8.6	5.0	12.7
23	Escuela Ave	Westbound	6.3	3.1	5.6	2.6	9.1	0.0	-3.7	6.0	-5.6
		Eastbound	32.0	10.5	50.0	38.6	11.9	52.2	6.6	1.4	2.2
25	Shoreline Blvd	Westbound	84.4	78.1	94.4	74.4	75.8	85.7	-10.0	-2.3	-8.7
		Eastbound	26.0	17.5	28.6	17.5	6.8	8.7	-8.5	-10.7	-19.9
26	Castro St	Westbound	34.4	59.4	27.8	12.8	57.6	50.0	-21.6	-1.8	22.2
		Eastbound	38.0	70.2	67.9	57.9	72.9	78.3	19.9	2.7	10.4
27	Calderon Ave	Westbound	12.5	31.3	22.2	10.3	33.3	7.1	-2.2	2.0	-15.1
		Eastbound	26.0	64.9	67.9	17.5	64.4	58.7	-8.5	-0.5	-9.2
28	Grant Rd	Westbound	53.1	75.0	44.4	51.3	51.5	78.6	-1.8	-23.5	34.2
		Eastbound	26.0	56.1	71.4	14.0	61.0	60.9	-12.0	4.9	-10.5

Table E-4 below compares the average stopped time at intersections for the “before” and “after” scenarios.

Table E-4: Comparison of Average Intersection Stopped Time

INT ID	Cross St	Direction	Average Stopped Time				T-test
			Before (sec)	After (sec)	Change (sec)		
					value	%	
2	Serra St	Westbound	0.04	2.09	2.06	-	0.1214
		Eastbound	2.04	8.44	6.41*	314.54*	0.0001*
4	Cambridge Ave	Westbound	11.67	11.05	-0.62	-5.35	0.3973
		Eastbound	0.65	1.55	0.90*	137.69*	0.0107*
6	Page Mill Rd	Westbound	37.12	21.24	-15.88*	-42.77*	0.0031*
		Eastbound	50.34	42.35	-7.99*	-15.87*	0.0075*
10	Curtner Ave	Westbound	1.12	0.91	-0.21	-19.16	0.3432
		Eastbound	1.42	1.57	0.15	10.24	0.4348
11	Los Robles Ave	Westbound	11.38	12.44	1.06	9.35	0.3526
		Eastbound	7.13	9.77	2.64	37.04	0.1621
12	Maybell Ave	Westbound	14.98	10.41	-4.57*	-30.51*	0.0409*
		Eastbound	10.82	5.96	-4.86*	-44.90*	0.0178*
13	Charleston Rd	Westbound	2.99	3.77	0.78	26.09	0.2919
		Eastbound	15.10	13.57	-1.52	-10.08	0.3024
14	Dinah's Court	Westbound	1.12	0.06	-1.06*	-94.82*	0.0330*
		Eastbound	2.75	2.44	-0.31	-11.28	0.3562
15	Los Altos Ave	Westbound	1.13	0.13	-1.01	-88.72	0.0677
		Eastbound	3.30	5.15	1.85	56.02	0.0769
16	Del Medio Ave	Westbound	0.50	0.40	-0.10	-20.93	0.4173
		Eastbound	2.57	2.19	-0.39	-14.99	0.3452
17	San Antonio Rd	Westbound	47.35	34.98	-12.38*	-26.14*	0.0042*
		Eastbound	9.36	7.98	-1.38	-14.75	0.2696
18	Showers Dr	Westbound	2.55	3.23	0.68	26.83	0.3326
		Eastbound	0.13	0.00	-0.13	-100.00	0.1596
19	Jordan Ave	Westbound	1.44	0.74	-0.69	-48.29	0.1848
		Eastbound	4.34	3.52	-0.82	-18.94	0.2399
20	Ortega Ave	Westbound	0.44	0.52	0.08	19.19	0.4510
		Eastbound	5.40	1.84	-3.56*	-65.94*	0.0004*
21	Distel Dr	Westbound	0.00	0.14	0.14	-	0.0449
		Eastbound	1.68	2.09	0.40	24.08	0.2990
22	Rengstroff Ave	Westbound	0.72	0.66	-0.06	-7.88	0.4660
		Eastbound	4.24	6.61	2.37*	56.03*	0.0306*
23	Escuela Ave	Westbound	0.46	0.72	0.26	55.57	0.3108

INT ID	Cross St	Direction	Average Stopped Time				T-test
			Before (sec)	After (sec)	Change (sec)		
					value	%	
		Eastbound	7.60	7.49	-0.11	-1.48	0.4777
25	Shoreline Blvd	Westbound	32.41	31.84	-0.58	-1.78	0.4357
		Eastbound	9.13	3.80	-5.33*	-58.40*	0.0131*
26	Castro St	Westbound	19.41	13.40	-6.02	-31.00	0.1032
		Eastbound	31.41	33.37	1.96	6.23	0.3073
27	Calderon Ave	Westbound	10.49	9.01	-1.48	-14.08	0.3244
		Eastbound	24.00	19.37	-4.63	-19.29	0.0639
28	Grant Rd	Westbound	36.28	25.10	-11.17*	-30.80*	0.0126*
		Eastbound	15.76	11.11	-4.65*	-29.51*	0.0362*

* Significant at 5% level of significance

E.1.1.3 Bus Trip Travel Time and Intersection Delay

Table E-5 below compares the trip based measures for the "before" and "after" scenarios.

Table E-5: Comparison of Trip MOEs

	MOE	Time-of-Day	Bus Travel Time & Intersection Delay						T-test
			Before		After		Change		
			Mean	SD**	Mean	SD**	Value	%	
WB	Travel time (min)	AM	17.99	1.92	17.50	1.47	-0.49	-2.8%	0.1187
		MD	19.28	2.78	17.35	2.31	-1.92*	-10.0%*	0.0018*
		PM	17.26	2.10	16.29	1.44	-0.96	-5.6%	0.0675
	Dwell time (min)	AM	1.31	0.49	1.44	0.86	0.14	10.5%	0.2015
		MD	1.24	0.58	1.05	0.53	-0.19	-15.4%	0.0870
		PM	0.92	0.38	0.85	0.38	-0.07	-7.6%	0.3066
	Stopped time (min)	AM	4.22	1.28	3.61	1.07	-0.61*	-14.4%*	0.0179*
		MD	4.85	1.51	3.66	1.31	-1.19*	-24.6%*	0.0006*
		PM	4.14	1.26	3.63	1.03	-0.51	-12.4%	0.1077
	Running time (min)	AM	12.47	0.73	12.44	0.67	-0.02	-0.2%	0.4469
		MD	13.19	1.17	12.65	0.88	-0.54*	-4.1%*	0.0198*
		PM	12.20	0.86	11.82	0.58	-0.38	-3.1%	0.0746
	Number of stops at red	AM	6.09	1.67	5.72	1.73	-0.38	-6.2%	0.1786
		MD	6.84	2.62	6.15	1.97	-0.69	-10.1%	0.1171
		PM	5.94	1.39	5.14	1.51	-0.80	-13.5%	0.0676

	Number of stops at TSP intersection	AM	5.19	1.38	4.64	1.56	-0.55	-10.5%	0.0612
		MD	5.84	2.03	5.24	1.77	-0.60	-10.3%	0.1044
		PM	4.94	1.21	4.29	1.33	-0.66	-13.3%	0.0797

EB	Travel time (min)	AM	16.71	2.44	15.83	1.59	-0.87*	-5.3%*	0.0166*
		MD	19.54	2.54	19.14	2.00	-0.40	-2.1%	0.1725
		PM	20.20	2.68	19.95	2.05	-0.25	-1.3%	0.3347
	Dwell time (min)	AM	1.62	1.93	1.16	0.64	-0.47	-28.7%	0.0543
		MD	2.83	1.34	3.58	1.60	0.75	26.3%	0.0037
		PM	1.73	0.72	1.74	0.77	0.01	0.4%	0.4832
	Stopped time (min)	AM	3.06	1.38	2.89	1.19	-0.17	-5.6%	0.2470
		MD	3.79	1.48	2.91	0.88	-0.87*	-23.0%*	0.0001*
		PM	4.57	1.70	4.42	1.33	-0.15	-3.3%	0.3471
	Running time (min)	AM	12.03	0.90	11.79	0.77	-0.24	-1.97%	0.0739
		MD	12.92	0.81	12.65	0.81	-0.28	-2.15%	0.0584
		PM	13.90	0.97	13.79	1.05	-0.11	-0.81%	0.3217
	Number of stops at red	AM	5.24	2.30	5.21	1.81	-0.03	-0.6%	0.4710
		MD	5.46	1.97	5.08	1.51	-0.37	-6.8%	0.1295
		PM	7.32	2.26	7.70	2.23	0.37	5.1%	0.2453
	Number of stops at TSP intersection	AM	4.42	2.10	4.47	1.77	0.05	1.2%	0.4438
		MD	5.25	1.88	4.75	1.48	-0.50	-9.5%	0.0579
		PM	6.64	2.11	7.22	2.11	0.57	8.6%	0.1304

* Significant at 5% level of significance
** SD stands for Stand Deviation

E.1.1.4 Examples of How Bus intersection delay is affected by Upstream TSP Executions

The receipt of successful TSP execution at upstream intersections affects the delay at the downstream intersection. For example, the average bus stopped time eastbound at Shoreline Blvd is 9 sec without TSP and 4 sec with TSP. Therefore a bus would arrive 5 sec earlier at Castro St upon receiving TSP execution at Shoreline Blvd. The time saving at Shoreline is valuable if the bus can catch the green at Castro, otherwise the bus has to stop longer due to the earlier arrival. The worst case scenario is an increased stop at Castro because of the TSP treatment received at Shoreline. The stop rate at Castro increased from 58% in "before TSP" to 69% in "after TSP". The 11% increase is due to the worst case scenario mentioned above. Although TSP executions at Castro reduced the average stopped time (if stopped) by 11% (from 54 seconds in "before TSP" to 48 seconds in "after TSP"), the average delay at Castro increased by 6% (from 31 seconds in "before TSP" to 33 seconds in "after TSP").

To understand the total trip time savings due to TSP operations, it is important to understanding the aforementioned example. Let $S_{i,j}$ be a dummy variable indicating whether a bus stopped at intersection j for trip i, i.e.,

- $S_{i,j} = \begin{cases} 0, \text{if bus stopped} \\ 1, \text{if bus not stopped} \end{cases}$
- and $T_{i,j}$ be the corresponding stopped time, i.e.,
- $T_{i,j} = \begin{cases} 0, \text{if } S_{i,j} = 0 \\ > 0, \text{if } S_{i,j} = 1 \end{cases}$

Then the average stopped time $\overline{ST}_j$ at intersection j, defined as the ratio of total stopped time to the total number of bus runs, is given by

- $$\overline{ST}_j = \frac{\sum_{i=1}^{N} T_{i,j}}{N} = \frac{\sum_{i=1}^{N} T_{i,j}}{\sum_{i=1}^{N} S_{i,j}} \times \frac{\sum_{i=1}^{N} S_{i,j}}{N} = ST_j \times SR_j$$

where SR_j is the stop frequency and ST_j is the average stopped time (if stopped) at intersection j. VTA TSP system is likely to reduce ST_j. However, Equation 4-4 clearly shows that the average stopped time $\overline{ST}_j$ is also affected by the stop frequency SR_j, which can be affected by TSP executions at upstream intersections. This is demonstrated in the following example.

Consider an eastbound bus trip between Shoreline Boulevard and Castro Street. Without TSP, the bus stops at Shoreline Boulevard with $T_1 > 0$, and it may or may not stop at Castro Street depending on the time the bus arrives at Castro Street, i.e., $T_2 \geq 0$. Upon receiving an early green treatment at Shoreline Boulevard, the stopped time is reduced to $(1-r)T_1$, and the bus arrives at Castro St rT_1 earlier than the without TSP case. The time saving ratio $r \in (0,1)$ for the early green treatment is 20% for VTA's TSP system.

There are four possible scenarios depending on the time the bus arrives at Castro Street:

Scenario 1:	The bus stops at Castro St for both with and without TSP
Scenario 2:	The bus dose not stop at Castro for both with and without TSP
Scenario 3:	The bus stops at Castro for without TSP but dose not stop for with TSP
Scenario 4:	The bus dose not stop at Castro without TSP but stops with TSP

TSP operations maintain the same number of stops at Castro Street under scenarios 1 and 2. The number of stops is reduced in scenario 3 and increased in scenario 4.

Figure E-1 illustrates the time-space diagram between Shoreline Boulevard and Castro Street in the eastbound during the morning peak. If the bus leaves Shoreline Boulevard during the first part of the green (between A and B), it will stop at Castro Street, i.e., arrives between 'A' and 'B' with a red signal.

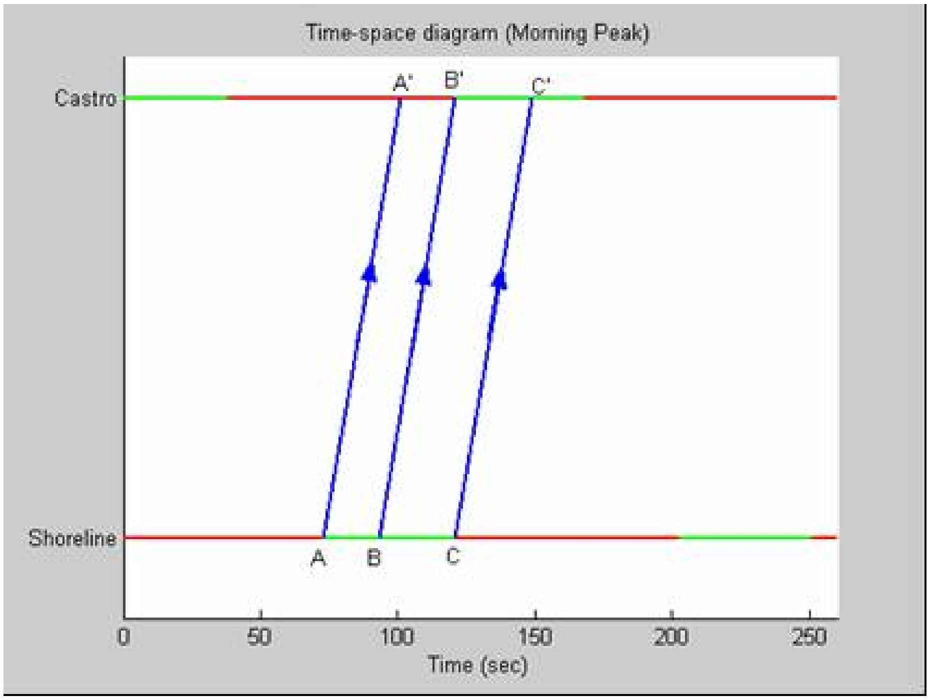


Figure E-1: Time-Space Diagram (Morning Peak)

Depending when the bus departs, there are four scenarios at Shoreline Boulevard:

Scenario 1: The bus leaves Shoreline between A and B for both with and without TSP

Scenario 2: The bus leaves Shoreline between B and C for both with and without TSP

Scenario 3: Dose not apply

Scenario 4: The bus leaves Shoreline between B and C without TSP, and between A and B with TSP

The corresponding four scenarios occur in mid-day peak:

Scenario 1: The bus leaves Shoreline between B and C for both with and without TSP

Scenario 2: The bus leaves Shoreline between A and B for both with and without TSP

Scenario 3: The bus leaves Shoreline between B and C without TSP, and between A and B with TSP

Scenario 4: Dose not apply

The green phase on the same bus direction starts earlier during the midday peak. If the bus leaves Shoreline Boulevard during the later part of green (between B and C), it will stop at Castro Street as shown in Figure E-2.

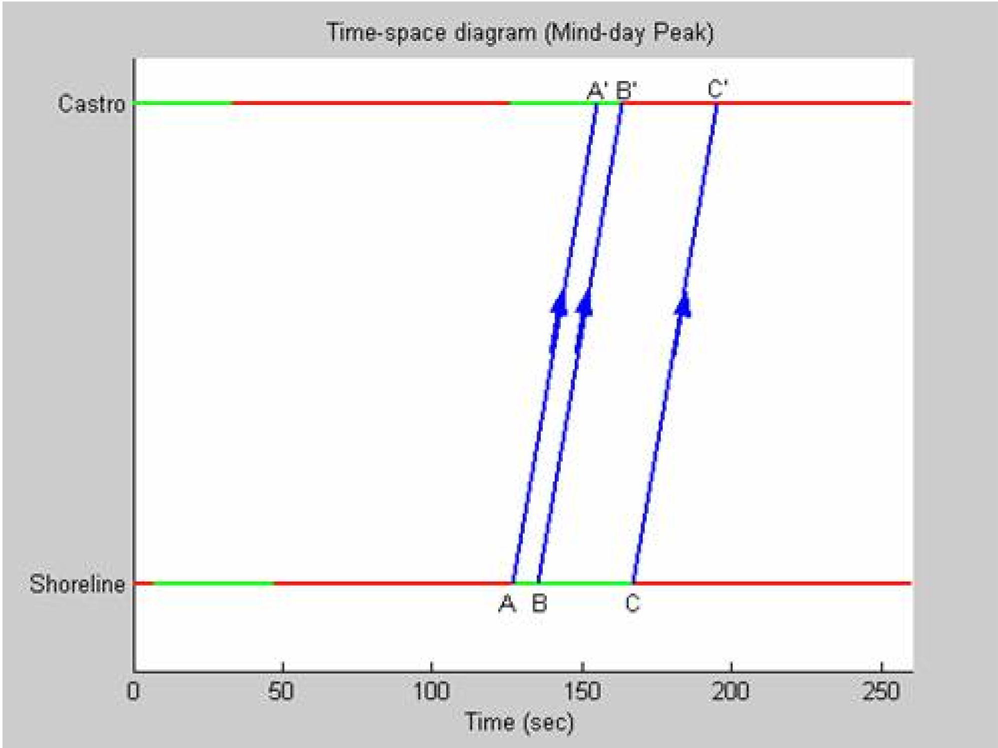


Figure E-2: Time-Space Diagram (Mid-Day Peak)

A comparison of the total stopped time in the morning and mid-day peak is presented in Table E-6 and Table E-7, respectively. The following observations can be made:

- If TSP operations maintain the same number of stops, the percentage of stopped time saving is between r^2 and r;
- If TSP operations reduce the number of stops, the percentage of saving is greater than r; and
- If TSP operations increase the number of stops, the percentage of saving is r^2.
- Note that only the stopped time is considered in the comparison. The lost time, e.g., the time bus decelerates to a stop and accelerates from a stop, is not included. For each increased stop, the lost time could be several seconds and that could lead to an increase in the total intersection delay.

Table E-6: Comparison of Total Stopped Time (Morning Peak)

Scenario	Without TSP			With TSP			Percentage of saving
	At Shoreline	At Castro	Total	At Shoreline	At Castro	Total	
1	T_1	$T_2 > 0$	$T_1 + T_2$	$(1-r)T_1$	$(1-r)(rT_1 + T_2)$	$(1-r^2)T_1 + (1-r)T_2$	$r^2 < \frac{r^2 T_1 + rT_2}{T_1 + T_2} < r$
2	T_1	$T_2 = 0$	T_1	$(1-r)T_1$	0	$(1-r)T_1$	r
3	-	-	-	-	-	-	-
4	T_1	$T_2 = 0$	T_1	$(1-r)T_1$	$(1-r)(rT_1)$	$(1-r^2)T_1$	r^2

Table E-7: Comparison of Total Stopped Time (Mid-day Peak)

Scenario	Without TSP			With TSP			Percentage of Saving
	At Shoreline	At Castro	Total	At Shoreline	At Castro	Total	
1	T_1	$T_2 > 0$	$T_1 + T_2$	$(1-r)T_1$	$(1-r)(rT_1 + T_2)$	$(1-r^2)T_1 + (1-r)T_2$	$r^2 < \frac{r^2 T_1 + rT_2}{T_1 + T_2} < r$
2	T_1	$T_2 = 0$	T_1	$(1-r)T_1$	0	$(1-r)T_1$	r
3	T_1	$T_2 > 0$	$T_1 + T_2$	$(1-r)T_1$	0	$(1-r)T_1$	$\frac{rT_1 + T_2}{T_1 + T_2} > r$
4	-	-	-	-	-	-	-

E.1.2 SamTrans TSP System

E.1.2.1 Summary of Testing Data

As shown in Table E-8, the total number of runs in the "before" and "after" scenarios is 143 and 110, respectively. These are spread out among morning, mid-day, and afternoon peaks.

Table E-8: Summary of Effective Bus Runs

Scenarios	Date		Effective Bus Runs			
			A.M.	M.D.	P.M.	Total
Before	1/23/2006	Monday	0	0	2	2
	1/24/2006	Tuesday	0	5	12	17
	1/25/2006	Wednesday	10	11	0	21
	1/26/2006	Thursday	12	12	9	33
	1/27/2006	Friday	9	6	6	21
	1/30/2006	Monday	2	3	15	20
	1/31/2006	Tuesday	8	9	12	29
	"before" total		41	46	56	143
After	2/1/2006	Wednesday	8	7	8	23
	2/2/2006	Thursday	10	8	13	31
	2/3/2006	Friday	7	7	6	20
	2/6/2006	Monday	4	6	13	23
	2/7/2006	Tuesday	4	0	0	4
	2/9/2006	Thursday	0	9	0	9
	"after" total		33	37	40	110
Total			74	83	96	253

Table E-9 illustrates the distribution of executed priority requests at the seven test intersections. For example, 12 trips requests priority at 9th Avenue. Five are early green requests and seven are green extension requests. All 12 trips are northbound. Three occur during the morning peak; five during the mid-day peak; and the remainder in the afternoon peak. The TSP execution rate is approximately 11%. Seventy percent of the trips do not need priority. That is, there is a 70% chance that a bus will arrive at 9th Avenue during the green period. The rate that TSP is not needed is estimated using 10 randomly picked trips. A total of 19% of priority requests at 9th Avenue are blocked. Most are blocked by protected signal control logic such as pedestrian call and minimum green. When the travel time predictor yields large prediction errors due to instability in communication or GPS system, TSP requests may be blocked by the PRG.

Barneson Avenue and 12th Avenue have execution rates that are less than 5% because of low traffic demand on the minor phases. Under semi-actuated signal control logic, green time is assigned to coordinated phases when there are no calls from minor phases. Buses have a better chance of catching the green phase at a signal with less traffic on the minor phases, and hence are less likely to need TSP.

The intersections at 17th Avenue and 25th Avenue have the heaviest traffic, and the TSP requests are higher than at other intersections. Moreover, 25th Avenue is a wide street connecting two shopping areas, and as such, has frequent pedestrian calls that result in a high block rate.

Table E-9: Distribution of Executed Priority Requests

		Number of Executed Priority Requests							
		9th Ave	12th Ave	Barneson	17th Ave	25th Ave	27th Ave	28th Ave	Total
Executed priority requests	EG*	5	0	3	31	27	8	6	80
	GE*	7	4	2	15	8	6	0	42
	NB*	12	2	5	22	17	0	5	63
	SB*	0	2	0	24	18	14	1	59
	A.M. *	3	1	1	7	9	3	1	25
	M.D. *	5	2	3	24	21	6	2	63
	P.M. *	4	1	1	15	5	5	3	34
	Total	12	4	5	46	35	14	6	122
% of all*	Executed	10.91%	3.64%	4.55%	41.82%	31.82%	12.73%	5.45%	15.84%
	TSP not needed*	70%	90%	70%	40%	20%	80%	80%	64%
	Blocked*	19.09%	6.36%	25.45%	18.18%	48.18%	7.27%	14.55%	19.87%

* Note:
EG: Executed early green requests;
GE: Executed green extension requests;
NB: Northbound trips with executed requests;
SB: Southbound trips with executed requests;
A.M.: Trips during morning peak with executed requests;
M.D.: Trips during mid-day with executed requests;
P.M.: Trips during afternoon peak with executed requests;
% of all: Percentage among total 110 testing trips;
TSP not needed: Trips where TSP requests are not needed;
Blocked: Trips which TSP requests are blocked.

E.1.2.2 Trip-Based MOEs

Based on the available data, the following transit vehicle related MOEs were selected for the evaluation:

- travel time on segment
- number of stops at red
- total intersection delay on segment
- maximum intersection delay on segment
- average delay per stopped intersection
- average traveling speed on segment

The test bus was not on a schedule and as such bus schedule reliability was not included in the evaluation.

The intersection at 20th Avenue is not TSP capable; however, TSP treatments from upstream intersections affect the measured delay. The trip-based analysis was conducted along the entire corridor, including 20th Avenue.

In order to include the delay at the intersections on either end of the corridor, the northbound segment has been defined from 31st Avenue to 9th Avenue (2,933 meters), and the southbound segment from 5th Avenue to 28th Avenue (2,954 meters).

The ATSP algorithm provides optimized green splits that facilitate the movement of in-service transit vehicles through signalized intersections while minimizing the negative impacts on normal traffic. The average execution rate of TSP treatments is 17% in both directions, i.e., 1.2 TSP treatments are granted per trip. One third of the granted priorities are green extension treatments. The other two third are early green treatments.

A comparison of the bus trips MOEs for the "before" and "after" scenarios are illustrated in Table E-10. A T-test was conducted to determine the significance of the change.

Table E-10: Summary of ATSP Impacts on Transit Operations

MOE	Direction	"before" scenario	"after" scenario	Changes (value)	Changes (%)	t-test
Travel time (sec)	Northbound	386.7	335.8	-51.0*	-13.2%*	0.0005*
	Southbound	347.8	315.8	-32.0*	-9.2%*	0.0061*
No. of stops at red	Northbound	3.5	3.4	-0.1	-3.7%	0.2869
	Southbound	3.8	3.5	-0.3	-8.2%	0.0802
Average traveling speed (m/s)	Northbound	13.8	15.3	1.5*	10.8%*	0.0010*
	Southbound	15.4	16.4	1.1*	6.9%*	0.0081*
Total intersection delay (sec)	Northbound	136.2	109.9	-26.3*	-19.3%*	0.0065*
	Southbound	125.6	107.4	-18.1*	-14.4%*	0.0248*
Maximum intersection delay (sec)	Northbound	57.4	46.5	-10.8*	-18.9%*	0.0482*
	Southbound	51.3	42.3	-9.1*	-17.6%*	0.0149*
Average delay per stop (sec)	Northbound	39.6	34.0	-5.6*	-14.1%*	0.0114*
	Southbound	33.4	30.6	-2.8*	-8.5%*	0.0074*

* Significant at 5% level

The noted bus time savings were achieved through an average of 1.2 TSP treatments per trip. As a result, the negative impact on cross street traffic is small. Moreover, granted priorities also benefit the mainline traffic.

Figure E-3 to Figure E-5 illustrate the empirical cumulative distribution functions (CDF) of bus travel time, average travel speed, and total intersection delay, respectively, for the "before" and "after" scenarios. The CDF plots show how ATSP operations reduce bus travel time and improve bus traveling speed.

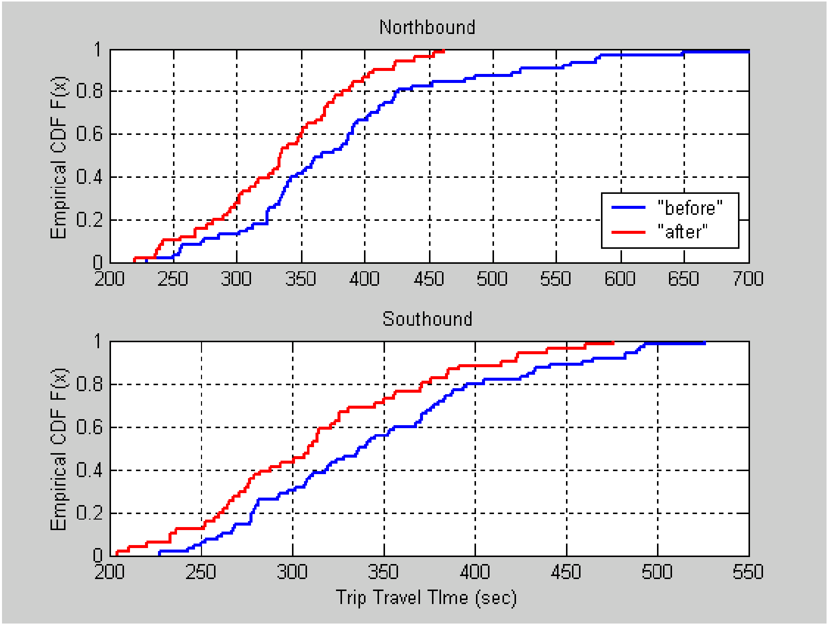


Figure E-3: CDF Plot of Bus Trip Travel Time

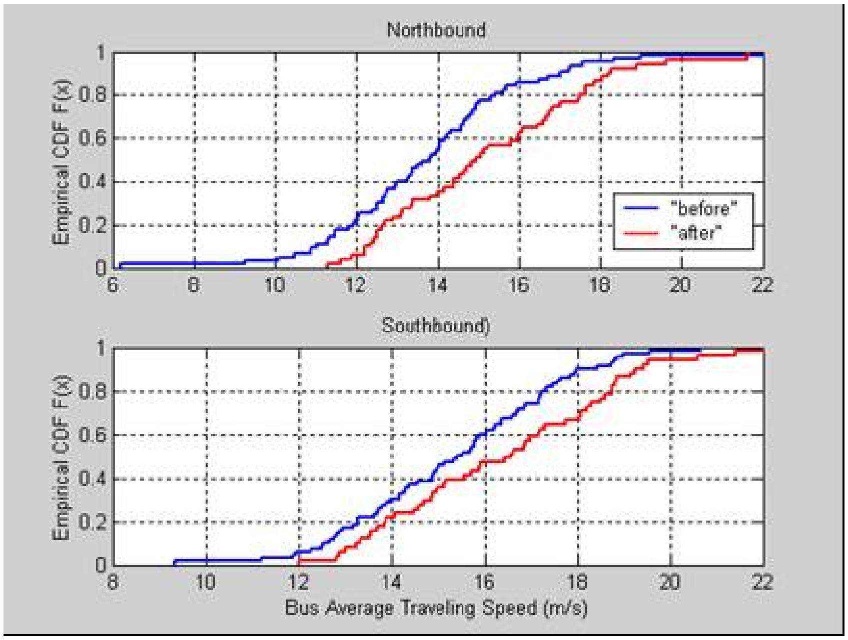


Figure E-4: CDF Plot of Bus Average Traveling Speed

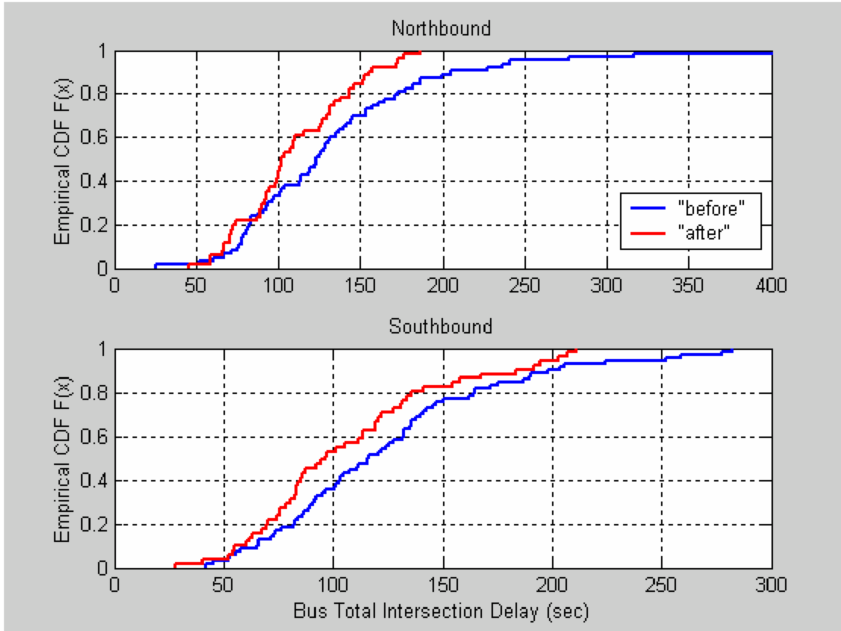


Figure E-5: CDF Plot of Bus Total Intersection Delay

At signalized intersections time is a critical resource, serving completing user needs. ATSP is an unconventional strategy to re-assign time resources among these parties, with transit vehicles have higher priority. The major concern of such treatments is how to better accommodate transit vehicles without significantly impacting the other parties. Intersection delay is one of the most important measures to evaluate ATSP impacts on all stakeholders.

E.1.2.3 Intersection-Based MOEs

Table E-11 compares intersection delays for "inferred before" and "after" scenarios. The "inferred before" scenario is not the same as the "before" scenario shown in Table E.10. Rather, the "inferred before" scenario has been estimated using the "after" scenario. ATSP algorithm re-assigns time resources (phase lengths) among different stakeholders. Without ATSP, the traffic signal will follow the original semi-actuated signal control logic and assign a cycle to different phases. A program has been developed to mimic the semi-actuated control logic and reverse the phase lengths in the "after" scenario with TSP to an "inferred before" scenario without TSP. The "inferred before" scenario can be more readily compared with the "after" scenario when the evaluation is conducted intersection by intersection and trip by trip.

According to the *Highway Capacity Manual 2000*, green splits are calculated based on the historical demand on the approaches. Therefore, green splits are the most appropriate approximate of the phase length. With the exception of coordinated phases, all phases under the "inferred before" scenario are assumed to be equal to or less than their green splits without pedestrian calls.

Delay data are retrieved by coding the actual phase lengths and traffic demands into the optimization model. The intersection delays for both the "inferred before" and "after" scenarios are calculated for local signal cycles, which consist of one background cycle and two control cycles, i.e. the adjacent signal cycle before the bus arrival, the bus arrival cycle and the following cycle. When calculating the average intersection passenger delay, the average number of passengers, including the driver, on a SamTrans bus is assumed to be 15.

At 9th Avenue the "inferred before" scenario has an average bus intersection delay of 41.6 seconds. The "after scenario" delay is reduced by 95%, to 1.98 seconds per bus. When evaluating the intersection passenger delays, the average passenger delay for all approaches, including buses, is reduced by 55% from 15.57 seconds per passenger to 6.98 seconds per passenger.

The 17th Avenue and 25th Avenue intersections are the busiest intersections along the corridor. The green time borrowed from the minor phases for buses and major phase traffic result in higher minor phase delay than observed at other intersections. The *weighting factor* balances the level of priority and hence the green time borrowed. In the field a constant weighting factor was applied at all seven intersections. In contrast, the TSP optimization model reduces the level of priority to buses at busy intersections in order to reduce the incurred minor phase delay. As illustrated in Table E-11, the average bus delay at 17th Avenue is reduced by 53% from 61.38 seconds to 28.56 seconds, and the average passenger delay is reduced by 14% from 25.93 seconds per passenger to 22.19 seconds per passenger. The statistics t-test shows that the passenger delay saving is statistically significant. Similarly at the 25th Avenue intersection, TSP results in a 43% reduction in the average bus delay and a 12% reduction in the average passenger delay, both of which are statistically significant.

The 27th Avenue and 28th Avenue intersections have less traffic on minor phases than the 17th Avenue and 25th Avenue intersections. With TSP, the average bus intersection delay and average passenger delay on 27th Avenue are reduced by 60% and 35% respectively, both of which are statistically significant. At 28th Avenue, the average bus delay and average passenger delay is reduced by 69% and 62% respectively. From the point of view of per passenger delay, the signal control efficiency is significantly improved.

Table E-11: Summary of ATSP Impacts on Bus Intersection Delay

	Delay (sec/veh or sec/pax)		Inferred "before" scenario		"after" scenario	
			Bus	Pax*	Bus	Pax*
9th Ave.	Mean		41.58	15.57	1.98	6.98
	Standard deviation		19.15	5.36	6.86	1.88
	Change	Sec/veh	N/A	N/A	-39.60	-8.59
		%	N/A	N/A	-95%	-55%
		t-test*	N/A	N/A	sig't*	sig't*
17th Ave.	Mean		61.38	25.93	28.56	22.19
	Standard deviation		19.49	7.34	29.64	7.60
	Change	Sec/veh	N/A	N/A	-32.82	-3.74
		%	N/A	N/A	-53%	-14%
		t-test*	N/A	N/A	sig't*	sig't*
25th Ave.	Mean		51.30	27.42	29.09	24.19
	Standard deviation		27.65	6.54	28.34	5.40
	Change	Sec/veh	N/A	N/A	-22.21	-3.23
		%	N/A	N/A	-43%	-12%
		t-test*	N/A	N/A	sig't*	sig't*
27th Ave.	Mean		45.35	19.13	17.93	12.36
	Standard deviation		17.49	7.52	21.74	4.30
	Change	Sec/veh	N/A	N/A	-27.42	-6.76
		%	N/A	N/A	-60%	-35%
		t-test*	N/A	N/A	sig't*	sig't*
28th Ave.	Mean		45.58	18.76	14.07	7.20
	Standard deviation		15.06	4.40	18.81	2.73
	Change	Sec/veh	N/A	N/A	-31.50	-11.56
		%	N/A	N/A	-69%	-62%
		t-test*	N/A	N/A	sig't*	sig't*

Note:
Pax*: Delay for passengers on buses and other vehicles;
t-test*: Statistic t-test to check the delay change is statistically significant or insignificant;
sig't*: Delay change is statistically significant;
insig't*: Delay change is statistically insignificant.

One of the major incentives for TSP is that transit vehicles carry more passengers than other vehicles, so that the appropriate priority to transit vehicles might reduce the overall passenger delay, which represents a more adequate measurement of effectiveness than the overall vehicle delay for traffic signal control at busy intersections. Table E-12 and Figure E-6 illustrate the results of a sensitivity analysis for passenger intersection delay with increasing number of passengers. The bus is considered empty when only the driver is on board.

Table E-12: Sensitivity Analysis of Passenger Intersection Delay (second/passenger)

Scenario	Number of pas	Passenger Intersection Delay (sec/passenger)						
		9th Ave	12th Ave	Barneson	17th Ave	25th Ave	27th Ave	28th Ave
Before	1 (empty)	14.35	6.49	16.40	24.37	26.78	18.20	17.94
	5	14.71	6.72	16.62	24.83	26.96	18.47	18.18
	10	15.14	7.00	16.89	25.39	27.19	18.80	18.47
	15	15.57	7.27	17.15	25.93	27.42	19.13	18.76
	20	15.98	7.52	17.41	26.46	27.64	19.44	19.04
After	1 (empty)	7.21	5.44	16.86	21.99	24.06	12.17	6.99
	5	7.14	5.35	16.70	21.99	24.10	12.22	7.05
	10	7.06	5.25	16.51	22.09	24.14	12.29	7.12
	15	6.98	5.15	16.32	22.19	24.19	12.36	7.20
	20	6.90	5.05	16.14	22.29	24.24	12.43	7.27
Change	1 (empty)	-7.13	-1.05	0.46	-2.38	-2.72	-6.04	-10.95
	5	-7.56	-1.37	0.08	-2.84	-2.87	-6.25	-11.13
	10	-8.09	-1.75	-0.38	-3.30	-3.05	-6.51	-11.35
	15	-8.59	-2.12	-0.83	-3.74	-3.23	-6.76	-11.56
	20	-9.08	-2.47	-1.27	-4.17	-3.41	-7.01	-11.77

Figure E-6 illustrates the percent passenger delay reduction at each intersection for increasing levels of bus occupancy. The slope of each curve represents the sensitivity of the passenger intersection delay reduction. The positive slopes indicate the delay savings associated with an increase in the number of passengers. Among the seven intersections, 12th Avenue and Barneson Avenue have the highest sensitivity. At these locations the traffic volume is small, and hence the bus weighs more heavily in the calculation.

Barneson Avenue data crosses zero percent delay reduction at approximately six passengers. Hence, the average passenger intersection delay will only be reduced when there are at least six passengers on the bus. At the other intersections, the re-optimized signal timing results in a reduction in the average passenger delay even though buses are empty. The existing semi-actuated signal control is less efficient.

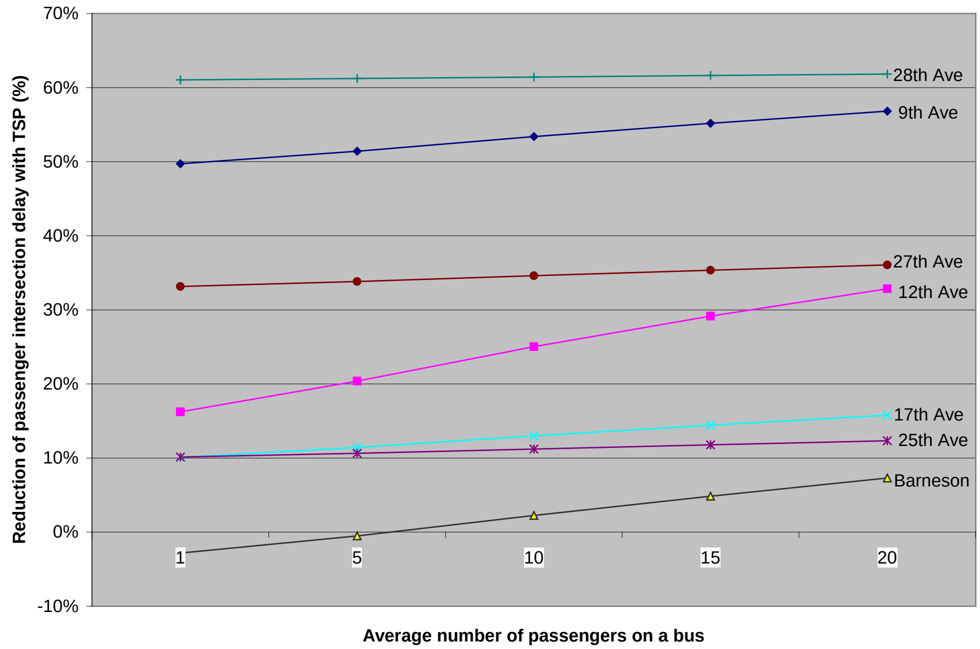


Figure E-6: Sensitivity analysis of passenger delay reduction (%)

E.2 TSP Impacts on Traffic

E.2.1 VTA TSP System

Table E-13 below compares the "before" and "after" traffic delay for five selected intersections, in terms of time-of-day.

Table E-13: Comparison of Traffic Delays for VTA TSP System

	Time of Day	Cambridge		Page Mill	
		Major	Minor	Major	Minor
Without TSP (sec/veh)	Morning	5.5	37.7	36.9	36.1
	Noon	9.8	39.2	33.5	44.7
	Evening	8.7	36.1	37.4	51.7
With TSP (sec/veh)	Morning	6.4	34.3	33.5	38.6
	Noon	9.3	37.2	31.7	48.4
	Evening	8.6	37.3	27.2	57.0
Change of Delay (sec/veh)	Morning	0.9	-3.4	-3.5*	2.5
	Noon	-0.5	-1.9	-1.8	3.6*
	Evening	-0.2	1.2	-10.2*	5.3
Percentage of Change	Morning	16.7%	-9.0%	-9.4%*	6.9%
	Noon	-4.8%	-4.9%	-5.4%	8.1%*
	Evening	-1.8%	3.3%	-27.4%*	10.2%
Significance of t-test	Morning	0.423	0.178	0.049	0.166
	Noon	0.702	0.398	0.319	0.011
	Evening	0.802	0.489	0.002	0.083

	Time of Day	Charleston		San Antonio		Jordan	
		Major	Major	Major	Minor	Major	Minor
Without TSP (sec/veh)	Morning	18.5	30.8	30.0	29.6	3.7	28.5
	Noon	17.6	31.7	36.4	29.6	6.4	25.6
	Evening	21.7	33.8	32.4	35.3	3.0	29.6
With TSP (sec/veh)	Morning	13.5	30.4	25.6	30.3	3.2	33.5
	Noon	16.8	32.4	26.7	29.4	6.7	29.2
	Evening	18.0	33.2	26.2	40.0	2.4	37.2
Change of Delay (sec/veh)	Morning	-5.0	-0.4	-4.4	0.7	-0.5	5.0
	Noon	-0.8	0.7	-9.6*	-0.3	0.3	3.6
	Evening	-3.7*	-0.6	-6.2*	4.8	-0.5	7.7
Percentage of Change	Morning	-27.1%	-1.4%	-14.6%	2.4%	-14.0%	17.4%
	Noon	-4.8%	2.3%	-26.5%*	-1.0%	4.7%	13.8%
	Evening	-17.0%*	-1.7%	-19.2%*	13.5%	-17.8%	25.9%
Significance of t-test	Morning	0.056	0.474	0.257	0.910	0.190	0.433
	Noon	0.599	0.286	0.020	0.847	0.389	0.313
	Evening	0.032	0.147	0.029	0.323	0.586	0.142

* Significant at 5% level of significance

E.2.2 SamTrans TSP System

To evaluate ATSP, intersection delay is one of the most important MOEs. Table E-14 compares intersection delays for “inferred before” and “after” scenario. The major signal phases are north and southbound along El Camino Real. Accordingly, minor phases are all phases except major phases. The intersection delays for both “before” and “after” scenarios are calculated using the local signal cycles, which consist of one background cycle and two control cycles, i.e. the adjacent signal cycle before bus arrival, the bus arrival cycle and its following cycle.

At 9th Avenue the “inferred before” scenario average major phase delay and the average minor phase delay are 4.16 seconds and 14.42 seconds, respectively. The “after” scenario average major phase delay is reduced by 81% to 2.70 seconds per vehicle. The minor phase delay is increased by 0.93 seconds per vehicle to 15.35 seconds per vehicle. The statistic t-test results show that the delay savings are significant, while the incurred delay for minor phase traffic is insignificant.

At 17th Avenue, the average major phase traffic delay is reduced by 14% from 33.20 seconds per vehicle to 28.48 seconds per vehicle. The increase in minor phase traffic delay is 1.49 seconds per vehicle. Similarly, 25th Avenue experiences a 16% decrease in the average major phase delay and an increase of 1.39 second per vehicle for minor phase traffic.

TSP at 27th Avenue results in a reduction of 36% in the major phase delays from 18.26 seconds per vehicle to 11.63 seconds per vehicle. The increase in the minor phase traffic delays are 1% and 0.21 seconds per vehicle. Negative impacts of TSP on minor phase traffic are minor. At 28th Avenue, the average delay saving for major phase traffic is 13.89 seconds per vehicle or a 74% reduction. The average minor phase traffic delay is increased by 3.53 seconds per vehicle delay which is statistically insignificant.

Table E-14: Summary of ATSP Impacts on Intersection Delay

	Delay (sec/veh or sec/pax)		Inferred "before" scenario		"after" scenario	
			Major	Minor	Major	Minor
9th Ave.	Mean		14.16	14.42	2.70	15.35
	Standard deviation		8.50	6.36	1.36	4.83
	Change	sec/veh	N/A	N/A	-11.46	0.93
		%	N/A	N/A	-81%	6%
		t-test*	N/A	N/A	sig't*	insig't*
17th Ave.	Mean		33.20	9.61	28.48	11.11
	Standard deviation		10.71	3.09	12.29	3.33
	Change	sec/veh	N/A	N/A	-4.72	1.49
		%	N/A	N/A	-14%	16%
		t-test*	N/A	N/A	insig't*	sig't*
25th Ave.	Mean		36.67	13.72	30.88	15.11
	Standard deviation		10.39	2.76	8.07	2.37
	Change	sec/veh	N/A	N/A	-5.79	1.39
		%	N/A	N/A	-16%	10%
		t-test*	N/A	N/A	sig't*	sig't*
27th Ave.	Mean		18.26	16.94	11.63	17.15
	Standard deviation		8.58	7.00	5.29	3.31
	Change	sec/veh	N/A	N/A	-6.62	0.21
		%	N/A	N/A	-36%	1%
		t-test*	N/A	N/A	sig't*	insig't*
28th Ave.	Mean		18.83	13.24	4.95	16.77
	Standard deviation		5.94	2.50	2.54	4.23
	Change	sec/veh	N/A	N/A	-13.89	3.53
		%	N/A	N/A	-74%	27%
		t-test*	N/A	N/A	sig't*	insig't*

Note:
t-test*: Statistic t-test to check the delay change is statistically significant or insignificant;
sig't*: Delay change is statistically significant;
insig't*: Delay change is statistically insignificant.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F	=	y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

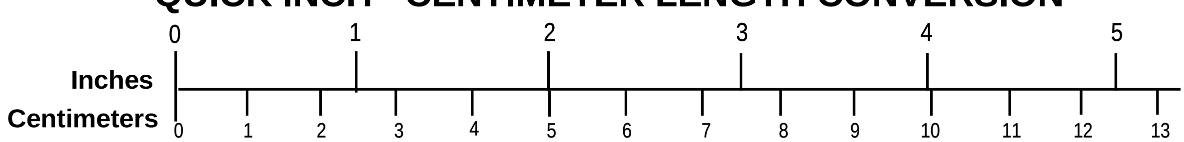
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

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Report Number: FTA-CA-26-7049-2008.1