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Control Strategies For Transit Priority

Author
Skabardonis, Alexander

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Alexander Skabardonis

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CONTROL STRATEGIES FOR TRANSIT PRIORITY

A. Skabardonis

December **1996**

ABSTRACT

Traffic control methods to provide priority to transit vehicles could improve transit operations, reduce operating costs and increase ridership. The report discusses the major factors influencing the benefits from transit priority and critically reviews existing control strategies implemented in signal controlled networks. **A** number of control strategies to improve transit performance are proposed along with an analysis technique to evaluate their effectiveness. The strategies were tested on a major arterial. Based on the results, recommendations are formulated for implementing transit priority strategies and development of improved analysis procedures for transit operations.

Keywords:
*transit, traffic signals, **preemption, traffic** control*

EXECUTIVE SUMMARY

Control strategies for transit priority has long been recognized of having the potential to improve traffic performance for transit vehicles that could also result in improved schedule reliability, reduce operating costs and attract ridership. However, there have been relatively few successful implementations of transit priority measures on urban networks with signalized intersections in coordinated signal systems. The study reviewed existing control strategies, identified the major factors affecting transit priority, and formulated both passive and active transit priority strategies. The proposed strategies were evaluated on a real-life arterial corridor.

Passive priority strategies, such as street designs to facilitate transit movements and transit weighted signal settings are generally low cost, easily implementable measures that are effective in simple network configurations, high bus frequency and predictable dwell times. However, most of the existing active priority strategies (signal preemption) were designed for isolated signals and cannot be readily implemented in a system with mostly fixed-time signals without substantial disbenefits to the rest of the traffic stream.

The proposed passive and active priority strategies developed in this study placed major emphasis on the systewide improvements to the transit movements (as opposed to a single intersection) and on minimizing the adverse impacts to the rest of the traffic stream. Preemption is granted when there is a spare green time in the cycle length to ensure that none of the traffic movements would become oversaturated. Additional criteria include progression at the downstream intersection(s), and schedule adherence.

Because existing simulation models cannot explicitly model most of the preemption strategies, an evaluation technique was developed in this study that can estimate the expected impacts of transit priority measures. This technique can be also used to assist in the design of the signal priority strategies.

The application of the proposed strategies on a major arterial with 21 signalized intersections showed modest improvements to the transit vehicles. Passive priority strategies improved bus delay by 14 percent, and signal preemption reduced delay by up to 6 seconds/intersection/bus. The disbenefits to the rest of the traffic stream were insignificant. These results apply to the specific site and could be higher on routes with higher bus frequencies. The proposed strategies also are implementable in most systems without adverse impacts to the auto traffic.

Improved capabilities in traffic control systems as part of the ATMIS and new transit technologies such as AVL/AVM systems offer considerable potential in developing effective control strategies for transit. There is a need to develop improved algorithms to take advantage of such technological advancements, comprehensive simulation tools for thorough laboratory evaluation of control improvements, and evaluation of proposed algorithms over a wide range of traffic and network scenarios.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Considerable attention is being given to the development of new approaches for improving the transportation system because of the limited funding and environmental concerns for constructing new highway facilities. One viable approach is implementation of advanced control strategies on arterials and grid networks. This would reduce unnecessary delays and stops at traffic signals, improve travel times, and cut fuel consumption and emissions. Surface streets could also serve as alternate routes for freeways during major incidents. In many instances these facilities also are major transit routes. Thus their efficient operation could be significant for transit **as** well as other traffic movements. In addition, transit priority measures could be implemented to maximize the passenger-carrying capacity of urban arterials and networks.

Priority to transit vehicles reduces travel times, improves service reliability, increases ridership and reduces the transit agencies' operating costs. Most of the control strategies for transit priority have applied to isolated signals with significant benefits to transit vehicles. Priority control in signal systems is not being implemented because in the past it has resulted in degradation of the overall traffic performance.

Advanced traffic management and traffic information systems (ATMIS) and new transit technologies as part of advanced public transportation systems (APTS) offer significant potential for systematically improving the operation of the existing transportation networks and at the same time provide priority to transit vehicles. Improved algorithms for transit priority could utilize the advancements in technology to provide transit priority without adversely impacting the rest of the traffic stream.

1.2 Objectives of the Study

The objectives of this study are to develop and evaluate strategies for transit priority in urban networks. Transit for the purposes of this study is defined as busses (and light rail) that share the roadway with other vehicles. Urban networks consist of arterials and grid systems that are controlled by traffic signals. The study addressed the following questions:

- What measures could be used to provide priority to transit under various operating conditions and control technologies?

- What are the impacts to transit and to the rest of the traffic stream that could result from those measures?

1.3 Organization of the Report

Chapter 2 reviews existing transit and traffic control systems technologies and discusses the strengths and weaknesses of existing transit priority strategies. Chapter **3** presents the study methodology including the formulation of the proposed strategies, analysis and evaluation plan, and the results from the application of strategies on a real-life corridor. Chapter **4** summarizes the study findings along with suggestions for future research. Appendix **A** includes a bibliography compiled from the literature search on control strategies for transit priority.

CHAPTER 2

BACKGROUND

This Chapter summarizes the findings from the review of the literature on strategies and systems for transit priority. Emphasis was placed on the latest developments in transit priority strategies and their relationship and role to the traffic control strategies for urban networks within the ATMIS context. Information was gathered via published sources on the application of, and experiences from, transit priority systems implemented in several metropolitan areas in the U.S. and abroad. Appendix A includes a bibliography compiled from the literature search. Additional information on relevant work in progress that is still unpublished was obtained via contacts with researchers and practitioners.

Transit priority measures fall into two major categories: those based on facility design and those relying on traffic control. Priority measures based on facility design normally consist of exclusive lanes for transit on arterials, as well as street designs to facilitate safe expeditious loading and reduce conflicts with transit vehicles entering and leaving the traffic stream. Priority measures relying on traffic control range from changes into fixed-time signal settings to favor transit, signal preemption at specific intersections, and system-wide priority based on integrated automatic transit vehicle location/monitoring (AVI/AVL) systems and real-time traffic control systems.

Table **2.1** illustrates the current status of control strategies for transit priority. Each strategy consists of a combination of transit and traffic control system technologies. These technologies and their application in the context of providing priority to transit vehicles are discussed below:

2.1 Transit Technologies

Design based measures for transit priority include bus stop consolidation or relocation. Installation of bus bulbs (widened sidewalks at bus stops), bus bays to facilitate safe loading and reduce delay and conflicts with busses entering and leaving the traffic stream. On-street parking management to ensure the availability of adequate curb space for busses. These measures are often used in combination with traffic control options (e.g., adjustments of signal offsets to accommodate bus travel times.) ***An*** example of such measures is the San Francisco's MUNI Transit Preferential Street Program (MUNI **1987).**

The effectiveness of such measures is largely site specific. While mostly low cost and easily implementable, the measures can create problems if installed in unsuitable locations. For example, bus bulbs can work well if there **is** sufficient road capacity for the traffic to pass the stopped bus, but it can contribute to long queues and delays if the bus blocks traffic.

TABLE 2.1 STRATEGIES FOR TRANSIT PRIORITY

TRANSIT TECHNOLOGY	TRAFFIC CONTROL SYSTEM TECHNOLOGY				
	OFF-LINE			ON-LINE	
	FIXED	ACT	1.5GEN	CENTRAL	DEC/AD
DESIGN					
PREEMPTION					
AVI/AVL/AVM					
AVI/TMC	▨	▨	▨		

▨ ***Infeasible strategy***

DEFINITIONS: TRANSIT TECHNOLOGY
DESIGN: Bus Stop relocations/consolidation, boarding bays, exclusive lanes/approaches
PREEMPTION:signal preemption through selective detection
AVI/AVL/AVM: On-board transit identification/monitoring systems can be used for preemption
AVI/TMC: On-board identification/monitoring systems interface with traffic management center
real-time prediction of transit arrival times

DEFINITIONS: TRAFFIC CONTROL SYSTEMS TECHNOLOGY
OFF-LINE: Preset Timings based on historical data
FIXED: fixed-time control
ACT: traffic actuated controllers in coordination
***1.5** GEN: Operator selection of plan based on real-time data*
ON-LINE SYSTEM: Traffic Responsive Control
CENTRAL: Central control of signals (SCOOT/SCATS/UTCS 2nd GEN)
DEC/AD: Decentralized/Adaptive control (OPAC/UTOPIA/PRODYN)

Signal preemption extends the green signal at the intersection approach until the transit vehicle is past or advances the start of the green. Preemption is implemented by using strobe light emitters on the transit vehicles and special light detectors at the signal (Opticom **3M** system), by radio frequency or special loop detectors (bus signatures). Signal preemption options include the following:

Phase extension: holds the green until the transit vehicle clears the intersection. The amount of additional green time granted by the preemption is preset in the controller (about **10** seconds).

Phase advance: early start of the green for the phase serving the transit phase. It may be also used to clear vehicles stored in front of the transit vehicle.

Special phase: signal phase activated by transit vehicles. This is normally used in combination with phase sequences to clear non-transit vehicles stored in front of the transit vehicle.

Phase skip: omit entirely phase(s) not serving transit movements to provide additional green time to transit serving phase(s)

"Lift" strategy: detection calls from vehicles on non transit serving phases are ignored for a time interval after the detection of a transit vehicle (Jacobson **1993).** This provides a quick return to the transit serving signal phase(s).

Because transit preemption disrupts the normal signal operation that could increase the delay to the rest of the traffic stream, the following options are often employed in the preemption control logic:

Compensation: additional green time is given to the non-transit phases to compensate for the loss of green during preemption. This compensation time may be given during the cycle immediately following preemption, or apportioned into more than one signal cycle.

Inhibit: Once preemption is granted, subsequent requests by transit vehicles are ignored for a user specified number of signal cycles.

Signal preemption generally works well for express busses, or when the majority of stops are on the farside. For nearside bus stops preemption through driver control is normally required because of the uncertainty about the vehicle's departure. Driver initiated preemption has been cited as adding a substantial burden to the driver, and may result in busses running ahead of schedule. Thus, drivers often do not activate the preemption option. Newer vehicle detection technologies, however, that use multiple detection points in the vicinity of the intersection make preemption from nearside bus stops acceptable. Examples of these systems include the Phillips VETAG system, the SAIC system used by Caltrans on the Coronado Bridge, and the Amtech system used in Texas and New York.

Automatic vehicle location and monitoring (AVL/AVM) systems provide the transit vehicle's location and speed via transmissions of location from on-board or off-board equipment. Such systems provide for increased dispatching and operating efficiency, improve service reliability, improve transit patrons safety and security and can provide inputs to traveller information and control systems. Currently, there are **28 AVL** systems operational in the US with an additional **36** systems being installed, an increase of over **100** percent in the last four years (Cassey **1996).**

The interface of such AVM/AVL systems with signal control systems theoretically permits anticipation of preemption needs and real-time, system-wide adjustments to signal timings from the traffic management center (TMC). Such systems have been implemented in several French cities (Marseille, Nancy, Nantes); information on a bus' location, distance from the intersection, and speed is transmitted from the bus **AVL** system to the TMC, which in turn decides if priority can be given at the signal (Gilles **1988).**

The critical factor for successful implementation of such systems is the accuracy about the transit vehicle location. Typical AVL/AVM technologies provide information about the transit vehicle location within **150-300** feet, which may be inadequate for use in signal preemption, which requires accurate information about the bus arrival time **(** preferably within **3** seconds). In France central traffic computer/bus monitoring systems reportedly have vehicle location accuracies within **30** feet, and other systems developed in Japan reportedly detect vehicles with accuracies of **6** feet. The **AVM** system used in the Turin's UTOPIA system has vehicle location accuracy of about **13** ft **(4** m) and the vehicle is polled for information every **10** to **15** second intervals (Nelson **1995).**

An advanced AVL system is being implemented in the State of Washington (Mowatt **1996).** This system would permit real-time monitoring of busses and interface with TMC and signal controllers to grant priority to busses. Criteria for granting transit priority at the intersection include amount of time that bus is behind schedule, bus occupancy (based on automatic passenger counter data) and impacts to signal coordination. The configuration of the proposed system is shown in Figure **2.1**

2.2 Traffic Control Technologies

Traffic signals along arterials and networks operate as coordinated to provide for progression of the major through movements. Most of the existing signal systems use fixed-time timing plans prepared off-line based on historical data ("first generation" strategy). These plans are implemented either by time of day (TOD), e.g., am, midday and pm peak periods, or they are selected based on volume and occupancy data collected from system detectors located in key locations of the network. The system operator may also override the timings based on real-time surveillance data. Fixed-time plans, however, cannot deal with the variability of traffic patterns throughout the day, and they become outdated because of the traffic growth and changes in traffic patterns.

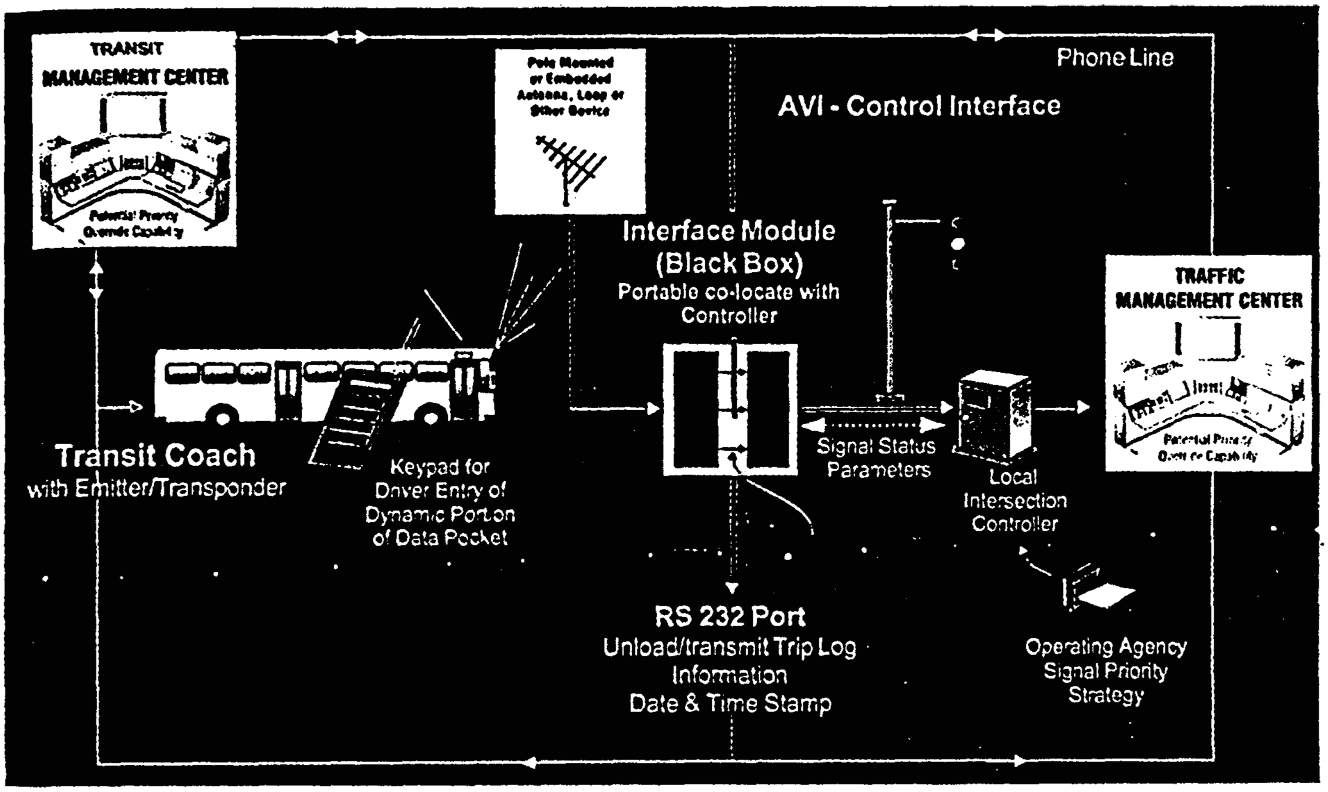


FIGURE 2.1 CONFIGURATION OF AN AVL/TRANSIT PRIORITY SYSTEM (Source: Mowatt 1996)

An increasing number of first generation control systems use traffic actuated controllers operating in coordination with a common background cycle length. These systems provide for improved through progression by utilizing the spare green time in the signal cycle from the "early" termination of actuated phases (Skabardonis **1996).** At the same time, they may reduce the total intersection delay by responding to the cycle-by-cycle fluctuations in traffic volumes. Simulation results and field studies have shown that coordinated actuated signals significantly improved the performance on the arterial at the expense of the cross-streets.

The "1.5 generation" control strategy first implemented in the city of Los Angeles ATSAC system (Rowe, **1987)** uses volume data from system detectors to update the approach volumes and update off-line the signal settings. The new plans are implemented by the system operator based on a comparison of the simulated performance from the new timings and the plan currently in operation. The verification and assessment of the timing plans prior to implementation ensures that the plans are operationally acceptable. This strategy reduces the effort to update timing plans, but still cannot respond to real-time changes in traffic patterns.

Transit priority is provided in off-line systems by determining the signal settings (cycle length, phasing, splits and offsets) to favor bus movements in the network. Examples include: shorter system cycle lengths to reduce delay, exclusive signal phases for transit vehicles, and setting the offsets between successive intersections based on the speed of busses and the dwell times at bus stops. Previous studies have shown that such timing plans can reduce travel times to transit vehicles by 5 to 8 percent with bus volume of 50 or higher, without adverse impacts to the rest of the traffic stream. The benefits were higher on arterials with high directional flows. The effectiveness of fixed-time plan for transit priority is reduced as the traffic patterns become more complex, and as transit dwell times become more variable (Yagar, 1989). *Also,* changes in bus volumes or routes could make these transit weighted timings ineffective.

Signal preemption has been widely applied at isolated signals and for LRTs, but there has been relatively little experience of preemption for busses in coordinated signal systems. In a UTCS experiment in the downtown Washington D.C. network, bus preemption was tested on **114** intersections with **300** instrumented busses (about 15 percent of the transit fleet). The travel times of the transit vehicles were reduced by about **6** percent but the total traffic performance was worsened (Kay 1975). Previous implementations of preemption have often resulted in loss of signal coordination and high delays to conflicting vehicle movements. Recent simulation studies also reported mixed results from bus preemption (Khasnabis 1996).

Most of the studies on bus preemption have focused on fixed-time signals. However, coordinated actuated signals would favor transit vehicles over fixed time signals since already incorporate several "preemption elements". For example, the signal controller reverts to the main street green in the absence of traffic demand on the actuated phases, i.e., provides additional green time which could be utilized by busses without the need for preemption. However, some preemption options cannot be easily incorporated into coordinated actuated controllers: green extension would result in loss of coordination because the end of the green for the through phase is controller's fixed coordination point.

Real-time Control Systems

"On-line" control systems update the timing plans in real-time based on data from detectors located on each intersection approach. Such strategies fall into two major categories: timing plan update (e.g., "UTCS Second Generation", SCATS and SCOOT) that adjust the signal settings while maintaining a common cycle length, and adaptive control policies (OPAC, PRODYN) that continually optimize the timings at each intersection over a short time interval (rolling horizon).

In the UTCS second generation control, the timing plans are prepared on-line and implemented approximately every 15 minutes. This strategy, however, **has** produced mixed results compared to fixed-time plans and it is not currently operational.

The SCATS (Sydney Coordinated Adaptive Traffic System) control system (Lowry 1982) uses detector data at the intersection stopline to measure the degree of saturation (volume/capacity ratio). It then adjusts on-line the background fixed-time plans. Transit priority in the SCATS system provides for green extension, special phase sequences and compensation to the non-transit phases (Cornwell, **1986).** Field tests have shown **6** percent travel time savings for Sydney's LRTs with insignificant disbenefits to cross street traffic.

The Splits-Cycle-Offsets-Optimization-Technique (SCOOT) method originally developed in England (Hunt **1981)** uses data from detectors located at the upstream end of each approach to estimate the size and shape of traffic platoons for each signal cycle. It then continually adjusts the timings to minimize the delays and stops. Evaluations indicate that SCOOT has reduced delay by **12** percent on the average over fixed-time plans. SCOOT has been implemented in 70 cities worldwide and currently is being installed in the city of Anaheim as part of an ATMIS field operational test.

Transit priority in SCOOT is provided by favoring the bus movements in the SCOOT optimizer, an approach similar to fixed-time control. The evaluation of this strategy in the field using instrumented busses did not show any statistically significant improvements (Wood **1992.)** The latest version of SCOOT provides for bus preemption including green phase extension and recall (Bretherton **1996).** Detection is provided through a special loop and transponders on the busses. Alternatively, AVL would transmit information on bus location, but it was found that is generally less accurate than the loop based detection. The preemption is granted based on user specified intersection degree of saturation to avoid excessive delays to the rest of the traffic. Field studies in London as part of the PROMPT project (Burton **1993)** showed average bus delay savings of 5 seconds/signal (about 22 percent improvement). Savings of about **10** sec/signal (70 percent improvement) were achieved in light traffic without disbenefits to the rest of the traffic stream.

Adaptive control systems use measurements from multiple detectors upstream of the intersection stopline to continually optimize the signal settings over a short time interval (rolling horizon), without necessarily maintaining a common cycle length in the network. Most of these approaches evolved from control of isolated intersections (MOVA, OPAC and PRODYN) and are still under development. The only operational adaptive control system with transit priority is to **UTOPIA** system in Turin (Davidsson **1992).**

The objective in the **UTOPIA** control logic is to provide absolute priority to transit vehicles and at the same time optimize the signal settings for the rest of the traffic stream. The AVL system monitors the bus location and requests from the TMC signal priority for busses that are delayed or designated having absolute priority. The estimated bus arrival time at the intersection is relayed to the controller and the signal settings are adjusted to accommodate the transit priority. The process is continuous and signal settings are reoptimized at each signal every **3** seconds. Reported benefits include a **20** percent increase in the average bus speeds without disbenefits to the rest of the traffic.

An adaptive signal control algorithm that incorporates transit priority has been recently proposed (Chang **1995).** Based on the rolling horizon concept, the signal settings are optimized every **3** seconds based on detector (or AVL) information on transit location. The optimization objective function includes bus delay, passenger delay and vehicle delay.

The algorithm was tested for an isolated intersection with simulated data and produced promising results. In another study, the OPAC algorithm was modified to optimize the signal settings based on the number of persons, instead of vehicle flows (Jacobson 1993).

23 Discussion

Control strategies for transit priority has long been recognized of having the potential to improve traffic performance for transit vehicles that could also result in improved schedule reliability, reduce operating costs and attract ridership. However, there have been relatively few success stories from the implementation of transit priority measures on surface street networks with signalized intersections in coordinated signal systems.

Passive priority strategies, such as street designs to facilitate transit movements and transit weighted signal settings are generally low cost, easily implementable measures that are effective in simple network configurations, high bus frequency and predictable dwell times.

Many operating agencies have resisted the implementation of bus preemption for several reasons. Most of the existing preemption strategies were designed for isolated signals and cannot be readily implemented in a system with mostly fixed-time signals without substantial disbenefits to the rest of the traffic stream. For example, phase skipping or red truncation could result in loss of coordination and high delays to the traffic platoons. Another issue is the assignment of priorities between intersecting transit lines in a grid network. *Also,* changes in signal phasing during preemption may potentially cause confusion to motorists. Furthermore, granting priority to a bus at an upstream intersection could result in additional bus delay at the downstream signal.

Improved capabilities in traffic control systems as part of the ATMIS and new transit technologies such as AVL/AVM systems offer considerable potential in developing effective control strategies for transit on a system basis that outperform the existing signal preemption algorithms. However, the evidence to date on the effectiveness of such systems is limited on simulation modeling of simple scenarios. *Also,* most of such technologies have high installation, operating and maintenance costs. Therefore, the implementation of such systems by operating agencies critically depends on clearly demonstrating their effectiveness over a range of conditions.

The effectiveness of transit priority strategies depend on the amount and the source of delay to the transit vehicles. If the delay at the signal is a small fraction of the overall transit route delay then the priority measures would not produce any noticeable improvements. Currently, there is a lack of comprehensive documentation of the effectiveness of transit priority measures over a wide range of traffic levels, network configuration, technology sophistication and bus volume and transit frequency and characteristics. Most of the studies reviewed are site specific and it is hard to generalize for planning and operations purposes.

CHAPTER 3

METHODOLOGY

3.1 Basic Considerations and Assumptions

The choice of the types of transit priority treatments to be used and the way(s) in which to deploy them, and their effectiveness depends on several factors including:

- **Network configuration and characteristics:** single arterial, grid network, signal spacing, number of lanes, pedestrian presence (e.g., in downtown areas). Type and operation of the traffic control system in place (fixed-time, traffic responsive).
- **Network traffic patterns:** traffic volumes, turning movements, variability in traffic volumes, level of congestion. Extend to which traffic congestion interferes with bus operations and the nature of the interference.
- **Frequency/characteristics of transit service:** bus volume, type(s) of bus operations (express or local), transit routes (e.g., conflicting bus movements at traffic signals), bus stop location/design, amount and variability of dwell times, and communication and monitoring equipment for transit vehicles.

An exhaustive study of these factors and their interrelationships was beyond the scope of the study. Emphasis was placed on developing transit priority strategies (as well as techniques for their evaluation where appropriate) for busses traveling along arterials. We assumed that there are no conflicting bus movements at the intersection approaches (that is busses travel sharing the roadway with the arterial through traffic and there are no transit vehicles on the cross-streets). Furthermore, transit vehicles do not block travel lanes at the intersection approach during loading and unloading times. Traffic signals are assumed to operate as coordinated with optimal timing plans for the prevailing traffic patterns. The implications of these assumptions are briefly discussed below:

The development of transit priority measures becomes very complicated when conflicting bus movements exist at the intersection. The strategy has to determine not only the type of priority over the automobile traffic but which of the conflicting transit movements should be given priority. For example, priority should be given to the busses running late subject to schedule maintenance for the other transit line. The development of such scenarios was beyond the scope of the present study.

Transit vehicles (especially streetcars) often block travel lanes at the intersection stopline during loading and unloading of passengers at nearside transit stations. This reduces the saturation flow at the intersection stopline and adversely affects the rest of the traffic stream, and reducing the potential of effective transit priority. In this study, it is recognized that bus presence has an impact on the saturation flow for nearside bus stops and it is modeled based on the procedures of the **1994** Highway Capacity Manual (TRB **1994).**

Signal operation under optimal signal settings under any type of signal control strategy (fixed-time or traffic responsive) was chosen as the baseline for evaluating the impacts of priority strategies. Several studies reported in the literature compared the effectiveness of transit priority measures against old coordinated timing plans or isolated signal operation. Such comparisons tend to mask the true impacts of a transit priority scenario because the improvements may be due to the changes in traffic control that also benefit the transit operation.

Finally, it is assumed that no incidents occur in the network throughout the evaluation of alternatives. Incidents (accidents, breakdowns and other random events) adversely affect the performance of the network and the effectiveness of any proposed strategies.

3.2 Development of Transit Priority Strategies

The development of transit priority strategies in this study took into consideration the existing control strategies and functions of traffic control systems, and the technologies for transit priority and information systems described in Chapter **2.** The proposed strategies fall into the following categories depending on the level of sophistication for control systems hardware and software (Table 3.1):

- optimal signal timing favoring transit vehicles (passive transit priority)
- bus preemption at intersections where busses would experience high delays through a combination of technologies (active transit priority)

3.2.1 Passive Priority Strategies

Passive priority strategies consist of methods for generating signal timing plans to favor transit along signalized arterials. These strategies may also involve bus stop relocation and/or consolidation, as appropriate, at specific locations. Some principles involved in the development of such strategies are shown in Figure 3.1.

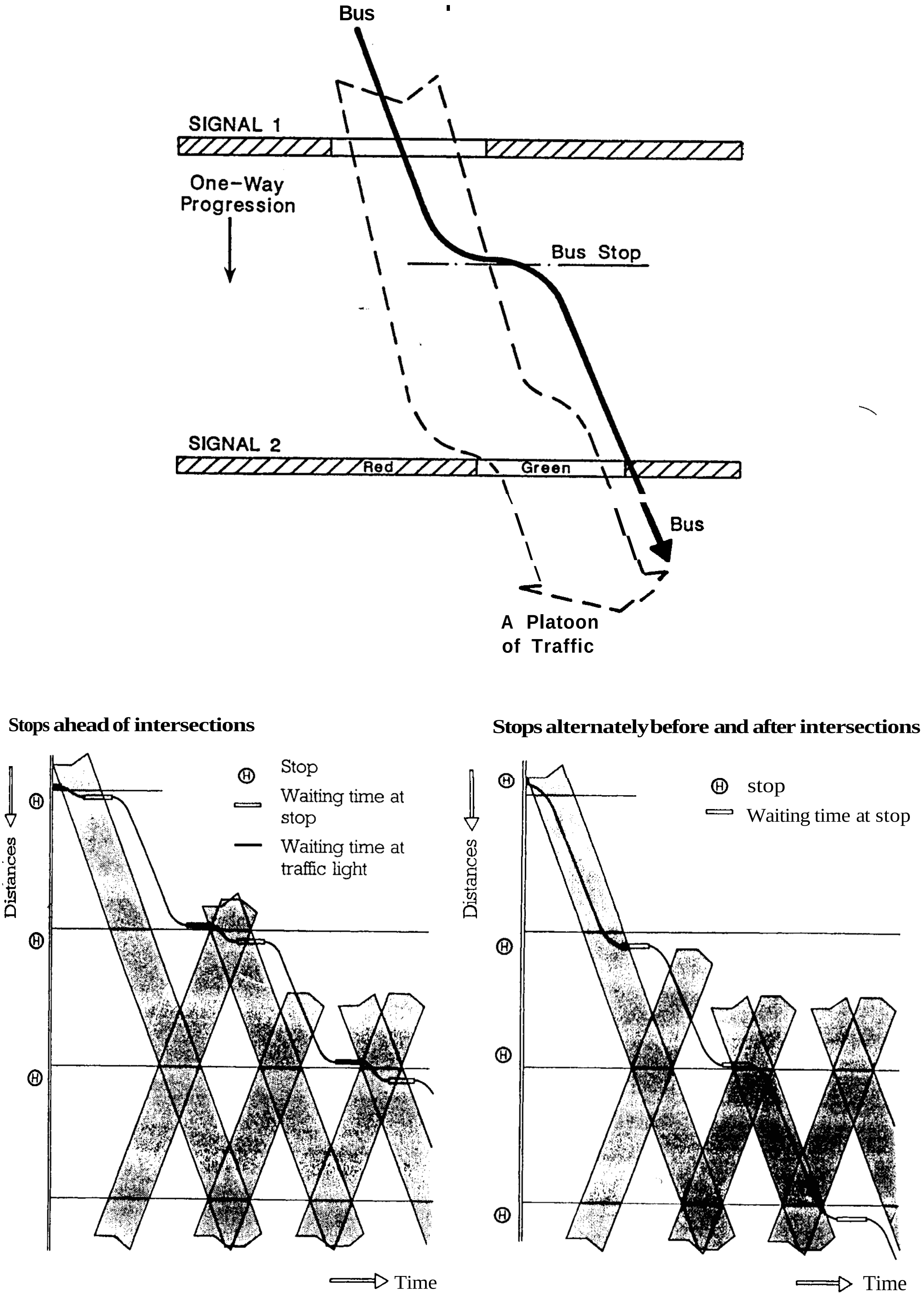
The top part of Figure 3.1 shows a time-space diagram between two signalized intersections and the trajectories of both a vehicle platoon and bus. To provide priority for busses the offset between the two signals should be adjusted to account for the slower speed of the bus and the midblock dwell time. The lower part **of** Figure 3.1 illustrates the effects of bus stop locations in designing a fixed-time plan to favor busses. Significant improvement for the progression of busses along the arterial can be achieved by alternating (if possible) the bus stop locations between the nearside and farside at successive intersections. In this case, busses would not have to stop at both the stopline (when the signal is red) and the bus stop.

The generation of the optimal timing plans (cycle length, green times and offsets) to favor transit vehicles can be accomplished by either manually modifying the background optimal timing plans based on bus service characteristics (as illustrated in Figure 3.1), or using a signal timing optimization program, e.g., TRANSYT-7F (Wallace 1992).

TABLE 3.1 SELECTED STRATEGIES FOR TRANSIT PRIORITY

TRANSIT TECHNOLOGY	TRAFFIC CONTROL SYSTEM TECHNOLOGY		
	OFF-LINE		ON-LINE
	FIXED TIME	ACTUATED	
NONE			▨
PREEMPTION			▨
AVI/TMC	▨	▨	

☐ Proposed Strategy
▨ Infeasible strategy



Stops ahead of intersections

Stops alternately before and after intersections

FIGURE 3.1 TRANSIT VEHICLE TRAJECTORIES

TRANSYT-7F is a macroscopic deterministic simulation and optimization model for signalized arterials and networks. It simulates the movement and interactions of traffic platoons and predicts several performance measures--MOEs (travel time, delay, number of stops, degree of saturation, maximum queue length and fuel consumption). **TRANSYT** can model a variety of network configurations, and vehicle classes (e.g., busses moving on exclusive lanes or sharing the roadway with the rest of the traffic.) Basic input data include traffic volumes, saturation flows, distances between intersections, cruise speeds and existing signal settings. The model uses an iterative optimization algorithm to optimize the system cycle length and the splits and offsets at each intersection to minimize the Performance Index--PI (a weighted combination of delays and stops):

$$PI = \sum_{i=1}^{N} W_{Di} D_i + K W_{si} S_i \qquad (3\text{-}1)$$

where:

N : ***number of links in the system***
W_{Di} : ***weighting factor for link delay***
D_i : ***total link delay (veh-h)***
K : ***the stop penalty (the weight of stops relative to delay)***
W_{si} : ***weighting factor for link stops***
S_i : ***number of stops on a link (#)***

TRANSYT-7F can be used to develop timing plans for transit priority as follows: bus movements are coded as separate links. Delay and stops weighting factors (WF) are then coded for the **bus** links ***so*** the signal optimizer would favor the transit vehicles compared to the rest of the traffic. The values of the WF in Equation **(3-1)** are often based on the ratio of occupancies of busses and passenger cars. For example, if the average vehicle occupancy is **1.3** persons/veh and the average bus occupancy is 25 persons/bus, then the value of the **WF** would be **(25/1.3 = 19).** This would be coded as **1900** in Record Types **37/38** in the TRANSYT-7F input file.

The choice of the WF depend on the bus volume, traffic patterns and network characteristics. For example, for low bus volumes (bus headways of **6** minutes or longer) very high values of weighting factors would have to be coded in order for the model to generate signal settings that provide measurable benefits to transit vehicles. *Also,* the trade-offs between the benefits to transit and the disbenefits to the rest of the traffic stream should be carefully evaluated. Figure **3.2** illustrates the sensitivity of traffic performance to the WF for a typical arterial with ten coordinated signals.

This Figure shows the predicted changes in delay and travel time compared to the base case of optimal signal settings for the existing traffic patterns. In Case **A** (bus volume of **10** busses/hr), the best transit priority settings are obtained for WF= **10000** (the maximum value accepted by the model). Benefits include a **13** percent delay reduction and **4** percent decrease in travel time for the transit vehicles, with a small disbenefit to the rest of the

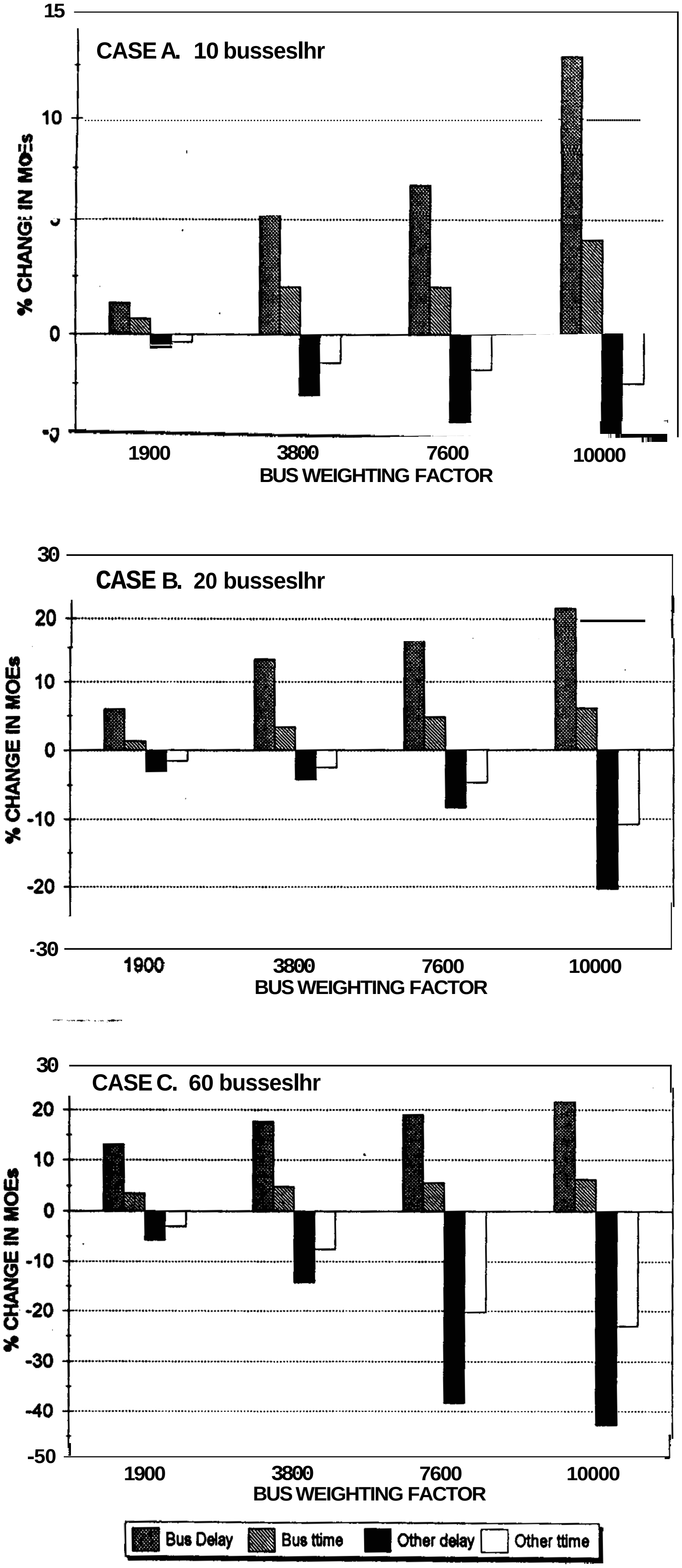


FIGURE 3.2 SENSITIVITY OF TRAFFIC PERFORMANCE TO TRANSIT PRIORITY traffic stream (about *5* percent delay increase). For higher bus volumes (Cases B and C in Figure 3.2), high values of WF would result in signal settings that seriously degrade traffic performance for vehicular traffic without additional benefits to transit vehicles.

Another issue in designing effective timing plans is the uncertainty of the **bus** arrival time at the intersection stopline because of the variability in transit dwell times, interference with other traffic and side friction along the link. Previous studies (Yagar 1989) have shown that high variability in dwell times may substantially reduce the benefits of transit weighted fixed-time plans.

3.2.2 Active Priority Strategies

The proposed active priority strategies (signal preemption and system-wide on-line adjustment of timing plans) consist of a) criteria for selecting specific intersections in the system to provide transit priority, and b) procedures for minimizing the adverse impacts to the rest of the traffic stream.

Criteria for signal preemption under the proposed strategy include the following:

- **Spare green time:** signal preemption may not result in oversaturated movements at the signalized intersection or result in **loss** of coordination. That is priority may be granted if there is sufficient spare green time in the system cycle length. The spare green time can be calculated as follows:

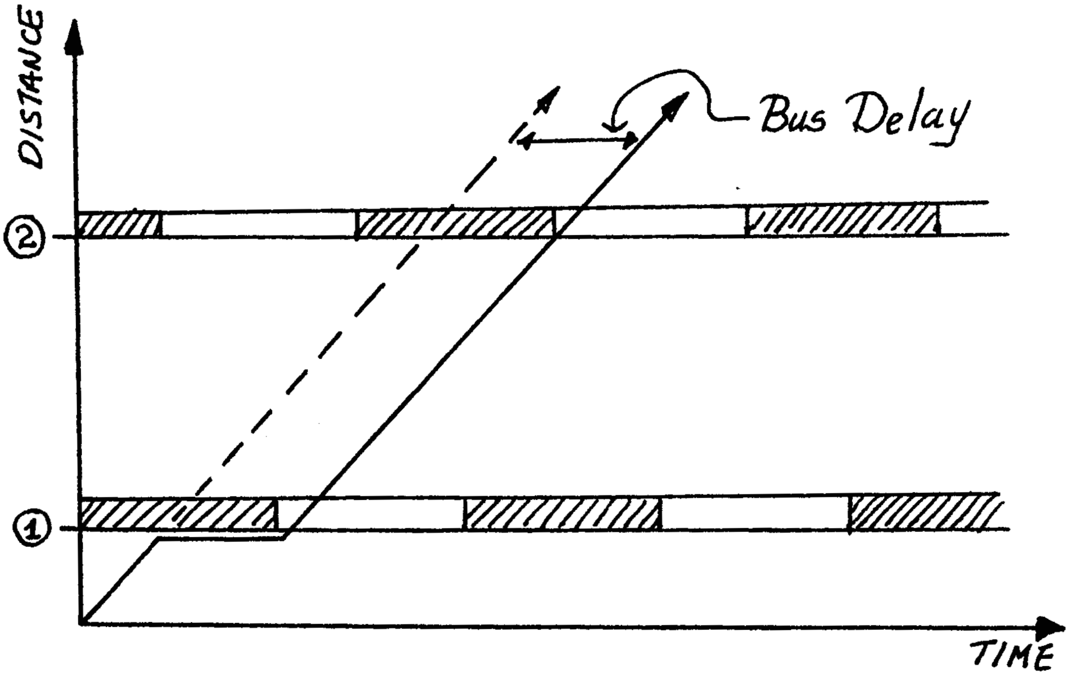
$$G_e = \sum_{1}^{N} G_i(1-X_i) \tag{3-2}$$

where:

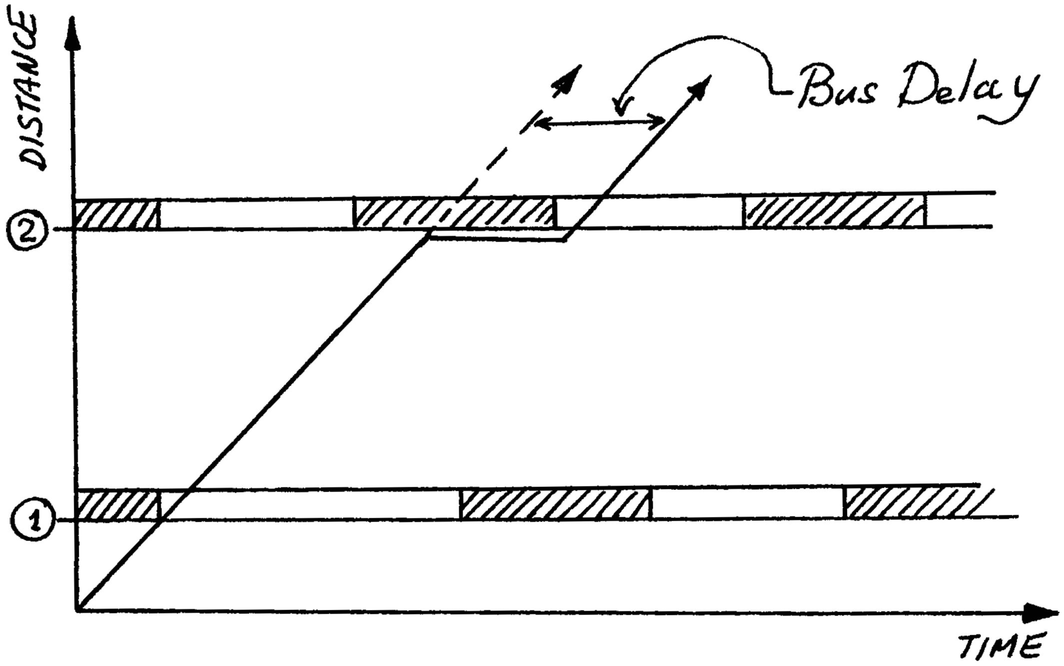
G : the spare green time
N : number of phases
G : green time **for** *phase i*
X : degree of saturation for the critical link moving on the phase i

- **Bus route progression:** The decision to grant preemption at an intersection should also consider the bus arrival times at the downstream intersection(s). For example, advancing the green time at the upstream intersection may result in additional bus delay downstream thus achieving no net delay benefit to the transit vehicles at a disbenefit to the rest of the traffic.

  Figure **3.3** shows an example of "wasted" bus preemption at the intersection **1.** Because the bus has to stop at the signal **2** downstream, the bus delay is the same as in the case of no preemption. Therefore, the signal settings (offsets) at the adjacent intersections) may need adjustments to account for the preemption effects. This



A. No Preemption



B. Bus Preemption -- Intersection 1

FIGURE 3.3 "WASTED" SIGNAL PREEMPTION

could be difficult to be implemented in off-line control systems with fixed-time plans unless busses arrive almost on each cycle. However, on-line control systems (such **as** SCOOT) should be able to make system-wide changes in the timing plans.

- **schedule adherence:** transit priority may result in busses being ahead of schedule, and some proposed strategies provide priority only to those busses that are behind schedule. However, favoring a "late-runner" bus may not be beneficial if it is empty and near the end of a route with an out-of service period to follow. This strategy would also require driver activated preemption, or accurate **AVL** systems to allow real-time determination of their location and status.

Suggested procedures to mitigate the adverse impacts of transit preemption include a) inhibit, i.e., limit the frequency of preemption by transit vehicles, and b) compensation, provide more green time to the non-priority traffic movements in the signal cycle(s) after the preemption. However, compensation does not work well in coordinated systems when the transit phase also serves the arterial through traffic. The additional green time given to the non-priority phase(s) would create large queues and delays to the through traffic.

The proposed criterion of spare green time in the cycle would prevent having high delays to the rest of the traffic stream. *Also,* it is proposed that the control logic includes a time-out option, which would terminate the preemption signal settings if the transit vehicle does not clear the intersection within a specified time interval because of randomness in loading/unloading or other incidents.

3 3 Evaluation of the Proposed Control Strategies

The proposed transit priority strategies were applied on a real-life corridor and their impacts evaluated separately for the transit vehicles and the rest of the traffic stream. The following performance measures (MOEs) were selected for use in the evaluation:

Impacts to transit: Travel time and delay to transit vehicles. In addition, schedule reliability and variation of bus headways will be assessed.

Impacts on the rest of the traffic stream: travel time, delays, and stops

Detailed analyses would compare performance on a) the total system, b) individual segments, and c) individual intersections. Such analyses are important because the impacts at a specific location might mask the overall effectiveness of a strategy, or vice versa. The performance of the strategies would also be compared under different traffic control technologies (offline .vs on-line control) to determine the benefits from enhancements in the TMC.

The development of the test plan for evaluation of the proposed strategies involved the following steps:

- selection of the analysis/evaluation techniques
- selection of the test site

33.1 Analysis Techniques

Existing analytical models to predict the impacts of bus priority with emphasis on signal preemption apply to isolated signalized intersections (Allsop 1977, Heydecker 1984). Recently, a number of models were proposed (Cisco 1995, Sunkari 1995) based on deterministic queuing theory and the delay equation in the 1994 Highway Capacity Manual. These models include several simplified assumptions on modeling traffic flow and signal operations and have shown poor agreement with field data.

A number of simulation models exist to simulate transit operations in urban networks. TRANSYT-7F may be used to evaluate the effectiveness of passive bus priority strategies, but it cannot directly handle real-time control systems and signal preemption. TRAF-NETSIM is a microscopic simulation model that models in detail individual vehicles including busses and various control strategies including fixed-time signals and vehicle actuated signals operating as isolated or coordinated. Model outputs include travel time, delay, stops, queue lengths, fuel consumption, and air pollutant emissions for each link and for the total system. Statistics are computed separately for autos and busses.

TRAF-NETSIM, however, cannot explicitly model signal preemption. One possible approach is to apply alternate fixed-time plans in successive time periods; one plan for normal signal operation, and the other plan simulates the preemption settings. This method has been applied (Al-Sahili 1996, Khasnabis 1996) as follows: the system was simulated with fixed-time plans. The animation routine of the model (ANETG) was used to view the simulated vehicle maneuvers on the computer screen and determine the bus arrival time at the intersection stopline. If the bus was delayed, the signal settings were adjusted (green extension or red truncation) ***so*** the bus would proceed without delay. The modified timings are then coded in the model as the plan for the next time period, and the system is resimulated for two time periods (signal cycles) to model the effects of "preemption". This process was repeated for all the intersections in the study area.

This approach may predict the impacts of transit preemption but it is tedious and time consuming. More important, it is infeasible to replicate the simulation process to account for random effects (for example, stochastic model variability, variability in bus loading and unloading times). Also, various control parameters (e.g., detector location, extension interval) cannot be tested because fixed-time plans are used to emulate preemption.

The TRAF-NETSIM's actuated controller logic may also be used to simulate preemption. Detectors are specified to sense the presence of a bus and initiate a call for service to the controller. This procedure can only be applied if the transit vehicles travel on exclusive lanes, e.g., LRTs on exclusive lanes parallel to the auto traffic with interactions only at the intersection stopline (Venglar 1995). Also, several preemption options cannot be tested. Only return to the transit phase (lift strategy) can be accurately simulated.

TRANSIMS II (Bauer 1995) is model specifically designed for testing signal preemption options. Transit vehicles are simulated microscopically but the rest of the traffic stream is simulated macroscopically. The model is proprietary, it has only been applied to model LRT operations, and it does not simulate non-transit vehicles in sufficient detail for operational analysis.

Development of an Analysis and Evaluation Procedure

An new procedure was developed in this study to evaluate the proposed preemption strategies. This technique is based on the widely used TRANSYT-7F model. The technique does not involve any software development; it utilizes several of the advanced features of the TRANSYT-7F model in successive model runs. The procedure consists of the following steps (Figure 3.4):

1. Optimize the signal timing plans (cycle length, splits and offsets) to minimize delays and stops for the total traffic stream. The model output represents the baseline conditions on traffic performance.

2. Select candidate intersections for signal preemption based on the criteria described in Section 3.2.2. Examine the flow-profiles output by the TRANSYT model to determine the bus arrival times in the cycle. If the bus is delayed, determine if spare green time is available to grant preemption. The spare green time is calculated from the Equation (3-2) using the degrees of saturation and green times for the critical links moving on each phase shown in the TRANSYT output.

3. Re-optimize the signal timing plans for absolute priority to the busses (preemption) at the intersections selected in Step **2.** This is accomplished as follows:

   Import the optimal timing plans developed in Step 1.

   Specify weighting factors of zero (0) for the auto links and the highest allowable value (10000) for the bus links on Record Types 37/38. The **TRANSYT** optimizer would then determine the signal settings for minimum delay and stops on the bus links ignoring the traffic performance of the rest of the traffic stream.

   Optimize the splits and offsets only for the intersections identified in Step **2.** The signal settings for the rest of intersections would be kept fixed by coding the intersection number as negative on Record Type 1X.

   Review the output of the optimization run to determine if further changes are needed to improve transit performance (e.g., offset adjustments to avoid wasted progressions.)

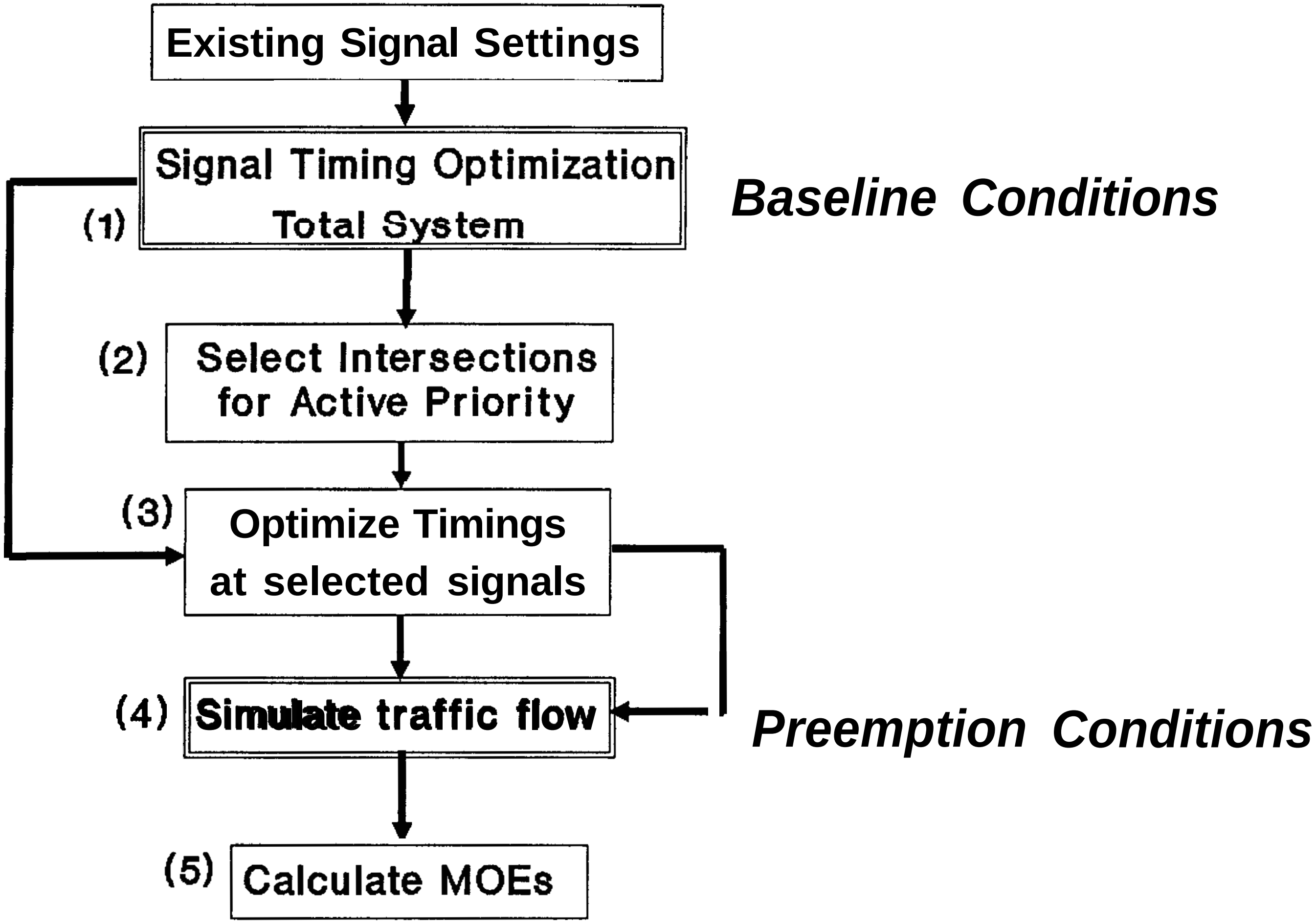


FIGURE 3.4 PROPOSED **EVALUATION PROCEDURE**

4. Code the changes in the signal settings from Step **3** into the basic TRANSYT file and perform a simulation run to predict the traffic performance. The output from this TRANSYT run represents the traffic performance under <u>preemution</u> conditions.

5. Calculate the performance measures (MOEs) for the traffic stream in the analysis period, as the weighted average of the MOEs for the signal cycles with and without signal preemption. For example, assuming that the bus volume is **10** busses/hr then the bus headways are **6** minutes. If the system cycle length is 80 seconds, then a bus would arrive about every 5 signal cycles, or about 11 percent of the cycles would include bus arrivals. The combined traffic performance would be:

$$MOE = a MOE_p + (1-a) MOE_{np} \tag{3-3}$$

where:
MOE: predicted performance measure (e.g., travel time, delay, stops)
a: proportion of signal cycles in the analysis period with bus arrivals
MOEp: predicted performance measure with preemption
MOEnp: predicted performance measure without preemption

This technique **is** simple and it can be used both to design and evaluate a bus preemption strategy. Comparisons with TRAF-NETSIM simulations show that it provides comparable results at much less time and effort. This technique can also be used to assess traffic responsive control strategies that are based on updating fixed-time plans. For example, the SCOOT logic is an on-line implementation of the **TRANSYT** optimizer and it can be modeled with this technique as a series of optimal timing plans per each time interval without the signal transition effects. Of course, this technique cannot explicitly model adaptive control systems that are not based on a common cycle length.

33.2 The Study Area

A segment of San Pablo Avenue a major urban/suburban arterial in the San Francisco Bay Area has ben selected as the test site for the evaluation of the alternative strategies. The segment is **6.7 Km (4.2** miles) long and includes **21** signalized intersections. It parallels the Eastshore 1-80 freeway and extends from the city of Oakland through the cities of Berkeley, Albany and El Cerrito. San Pablo serves as an alternate route to the 1-80 freeway during the peak periods and also carries a significant number of local and express busses.

Throughout the arterial there are four travel lanes plus turning bays on each intersection approach. Table **3.2** provides information on signal spacing, intersection characteristics and signalization. Approximately **60** percent of the signals are multiphase, **9** with protected left turns on the arterial and three with protected left turns or both the arterial and the cross-street. Traffic patterns range from predominantly through travel along the arterial with minor streets, to a grid of arterial and major cross street movements. The pm peak period was selected for evaluating the alternative strategies. The majority of the through traffic is northbound, especially at the northern sections of the study area.

Basic geometric, traffic, and control data of the study area were available from previous PATH studies and were already coded for the TRANSYT-7F and TRAF-NETSIM models. The database and input files were updated based on field checks in the study area to reflect recent changes to signalization and design modifications at several intersections (e.g., addition of protected left turn phases, and turning lanes). Information on transit service was assembled including bus routes, frequencies and bus stops, and the data were coded into the simulation models. Several debugging computer runs were made to ensure that the models are working correctly.

Comparisons of simulation runs with field measurements provided by Caltrans on five critical intersections along the study segment, indicate that the models reasonably represent existing operating conditions; most of the paired comparisons are within **10** percent of each other, and all correspond to the same level of service **(LOS).**

TABLE 3.2 SIGNALIZED INTERSECTIONS ALONG THE SAN PABLO TEST SITE

INT #	CITY	STREET NAME	SPACING (ft)*	T-INT	# LANES CROSS-STR**	# PHASES
1	OAKLAND	Stanford			2(1)	8
2		**63rd** Street	1690		1	**4**
3		Alkatraz	590	X	2	4
4	BERKELEY	Ashby	1943		3(1)	4
5		Grayson	1631	X	1	2
6		Dwight Way	1835		2	2
7		Allston Way	1980		1	2
8		Addison	520	X	1	2
9		University Ave	450		3	a
10		Delaware	977		1	4
11		Cedar	1300		3(1)	2
12		Gilman	1983		2	4
13		Monroe Ave	1620	X	1	**4**
14	ALBANY	Marin	760		2(1)	8
15		Buchanan	400	X	1	2
16		Solano Ave	420		2	**4**
17		Washington	790	X	1	2
18		Clay	1410	X	1	2
19		Brighton	240	X	2	2
20	EL CERRITO	Carlson Blvd	870		3	4
21		Fairmount	630		2(1)	4

NOTES:

****xxxx: Distance to the previous signalized intersection***

*****X(Y): Total # of lanes on the critical approach (# of exclusive lt lanes)***

4-phase signals: protected LT on the arterial (incl 3-phase at T-intersections)

8 phase: protected LT on the arterial and the cross-streets

3.4 Application and Results

This section presents the findings from the application of the proposed transit priority strategies on the San Pablo Avenue test arterial.

3.4.1 Passive Priority Strategies

First, alternative bus stop locations were tested along with alternative signal settings, and their impacts were examined by examining the TRANSYT flow profiles for the bus links, which provide information on bus arrivals at each signal. Next, transit weighted signal timing plans were developed using the **TRANSYT-7F** model. The results are shown in Figure 3.5.

Optimal timing plans to favor busses along the arterial reduced the delay to busses by **14** percent and improved the average bus speed by **3.4** percent. This translates into delay savings of about 2 seconds/bus/intersection. The impacts on the rest of the traffic stream were marginal. The total delay increased by 1 percent and the number of stops actually decreased by **2** percent. Most of the delay increase occurred on the cross-streets and left turn movements. The delay and stops for the through arterial links were slightly decreased because the transit weighted signal settings provide additional green time for the arterial through traffic.

These results apply for the baseline conditions: bus volumes of 10 busses/hr **(six** minute headways) and average dwell times of **16** seconds. Sensitivity analyses were performed by assuming different bus frequencies and durations of dwell times. The simulation results showed that the estimated transit improvements are insensitive to a range of bus volumes up to **30** busses/hr.

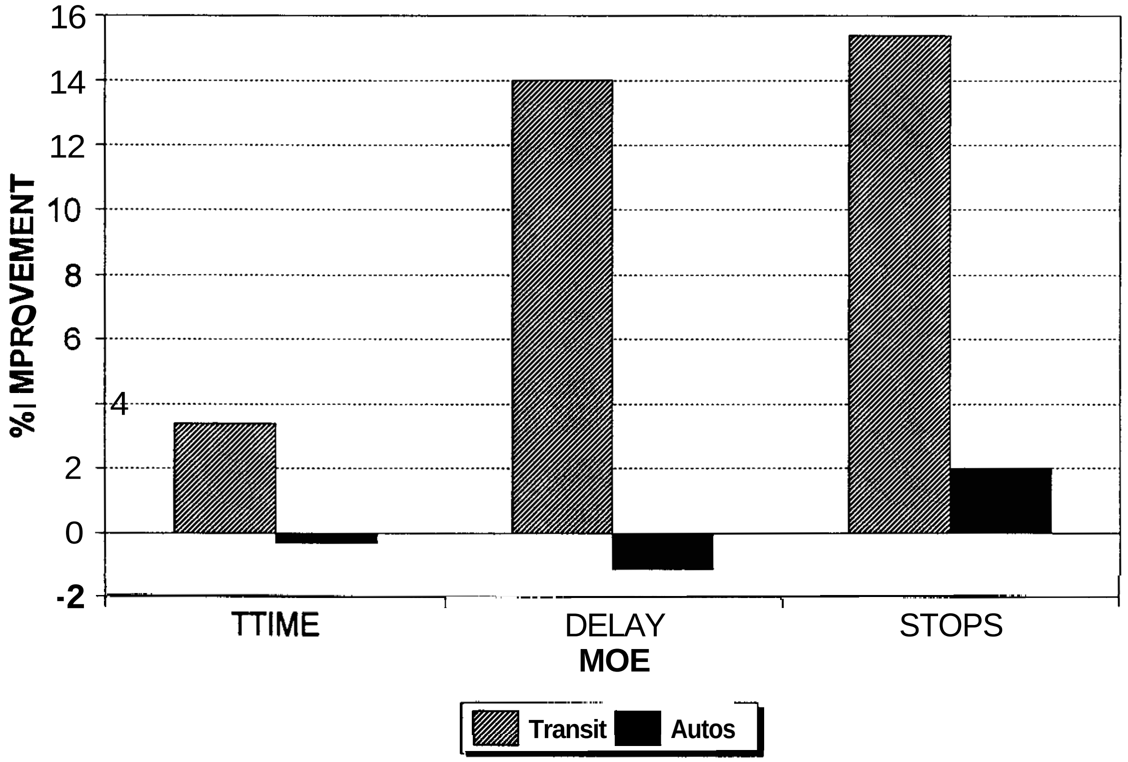
3.4.2 Active Priority Strategies

The evaluation of bus preemption at specific signals with offline fixed-time timing plans showed that bus time savings of 0 to **6** seconds per intersection could be achieved, with typical savings in the 0 to 2 seconds range. Over the study area, the savings from preemption at the selected intersections would be about two minutes. The impacts to the rest of the traffic stream were insignificant.

The active priority strategies tested were based on the criterion of spare green time to minimize the adverse impacts to the rest of the traffic stream. Higher benefits from preemption would result if busses would preempt any of the intersections that are delayed. Tests of this approach showed that it produced excessive queues on several side streets, and it appeared to lead to discharge of buses and other vehicles from the front of one queue only to deliver them to the back of the next queue. Such an approach is not likely to be implementable in real-life systems.

FIGURE 3.5 PASSIVE TRANSIT PRIORITY

SAN PABLO AVENUE: 21 SIGNALS (4.2 m)



The analysis of the simulation results on individual arterial links showed that signal delay was only about **20** percent of total bus delay; queuing delays during green lights and passenger loading/unloading delays also were noted. Such delays were confirmed through field observations. In many cases, much of the transit delay would not have been avoided by signal preemption.

Sensitivity analyses indicate that the results would not change significantly at most intersections even which substantial increases in bus frequency. The effectiveness of preemption at the study corridor is limited because a) at several intersections, buses travel through on the cross streets as well as along San Pablo Avenue, which offsets some of the advantage of giving priority to the San Pablo Avenue busses; and c) several intersections with spare green time (low, volume cross streets) operate as coordinated-actuated and already provide all the available green to the arterial in the absence of pedestrians.

Exploratory analyses of system-wide transit priority based on on-line signal control, plus AVL/AVM technologies added to transit, did not show significant improvements over the preemption with fixed-time plans. However, these results are conservative because the evaluation technique (or any other existing model) cannot explicitly simulate the performance of real-time systems.

CHAPTER 4

CONCLUSIONS

4.1 Summary of the Study Findings

Control strategies for transit priority has long been recognized of having the potential to improve traffic performance for transit vehicles that could also result in improved schedule reliability, reduce operating costs and attract ridership. However, there have been relatively few successful implementations of transit priority measures on urban networks with signalized intersections in coordinated signal systems. The study reviewed existing control strategies, identified the major factors affecting transit priority, and formulated both passive and active transit priority strategies. The proposed strategies were evaluated on a real-life arterial corridor. The major study findings can be summarized as follows:

- Passive priority strategies, such as street designs to facilitate transit movements and transit weighted signal settings are generally low cost, easily implementable measures that are effective in simple network configurations, high bus frequency and predictable dwell times. Most of the existing preemption strategies were designed for isolated signals and cannot be readily implemented in a system with mostly fixed-time signals without substantial disbenefits to the rest of the traffic stream.

- Existing simulation models cannot explicitly model most of the active preemption strategies. **A** simple evaluation technique was developed in this study that can produce similar results as other simulation models with much less time and effort. This technique can be also used to assist in the design of the signal priority strategies.

- The proposed passive and active priority strategies developed in this study placed major emphasis on the systewide improvements to the transit movements (as opposed to a single intersection) and on minimizing the adverse impacts to the rest of the traffic stream.

- The application of the proposed strategies showed modest improvements to the transit vehicles. These results apply to the specific site and could be higher on routes with higher bus frequencies. The proposed strategies also are implementable in most systems without adverse impacts to the auto traffic.

4.2 Future Research

Improved capabilities in traffic control systems as part of the ATMIS and new transit technologies such as AVL/AVM systems offer considerable potential in developing effective control strategies for transit that outperform the existing signal preemption techniques. However, the evidence to date on the effectiveness of such systems is limited based only on simulations of simple scenarios. *Also,* most of such technologies have high installation, operating and maintenance costs. Therefore, the implementation of such systems by operating agencies critically depends on clearly demonstrating their effectiveness over a range of network and traffic conditions. The following are immediate research needs for transit priority:

- Modeling: there is a need to develop improved simulation models that can explicitly simulate existing and future active transit priority strategies. This would allow the systematic laboratory evaluation of proposed strategies prior to implementation.

- Improved strategies: There is a need to develop improved algorithms for transit priority that take advantage of the data availability and communications of real-time control and transit systems.

- Application and Evaluation: Comprehensive documentation of the effectiveness of transit priority measures over a wide range of traffic levels, network configuration, technology sophistication and transit service characteristics. This would provide operating agencies with clear guidelines on which strategies to implement, expected benefits and associated capital, operating and maintenance costs.

REFERENCES

1. Allsop, R.E., **1977,** "Priority for Busses at Signal Controlled Junctions: Some Implications for Signal Timings," Proceedings 7th International Symposium on Transportation and Traffic Theory, Kuoto, Japan

2. Al-Shalili, **K.,** and **W.** C. Taylor, **1996,** "Evaluation of Bus Priority Signal Strategies in Ann Arbor, Michigan," Transportation Research Record # **1554.**

3. Bauer, T., et al, **1995,** "Testing of Light Rail Signal Control Strategies by Combining Transit and Traffic Simulation Models," Transportation Research Record **#1494.**

4. Bretherton, D., **1996,** "Current Developments in SCOOT: Version 3," Transportation Research Record **#1554,** pp. **48-52.**

5. Burton, R.S., **1993,** "Integration of Public Transport Vehicle Priority with Urban Traffic Control, Project PROMPT," Advanced Transport Telematics, Proceedings of the DRIVE Technical Days, Brushels.

6. Cassey, R.F., et al, **1996,** "Advanced Transportation Systems: The State of the Art Update **'96,**" Report FHWA-JPO-96-0033, Federal Transit Administration, Washington, DC.

7. Chang, G.L. et al, **1995,** "Bus-Preemption Under Adaptive Control Environments," Transportation Research Record No. **1494.**

8. Cisco, B.A., and **S.** Khasnabis, **1995,** "Techniques to Assess Delay and Queue Length Consequences of **Bus** Preemption," Transportation Research Record No. **1494.**

9. Cornwell, P. R., **1986,** "Tram priority in SCATS," Traffic engineering & control. Vol. **27 (11).**

10. Davidsson, F, **1992,** "Priority for Public Transport using Advanced Transport Telematics," Proceedings 3rd International Conference on Vehicle Information and Navigation Systems, **Oslo,** Norway.

11. Gilles, D., **1988,** "the French Experience with AVL in Urban Transportation Systems," Proceedings, International Conference on Automatic Vehicle Location in Urban Transit Systems, Ottawa, Canada.

12. Heydecker, B.J., **1984,** "Delay at a Junction where There is Priority for Busses," Proceedings 9th International Symposium on Transportation and Traffic Theory, Delft, Netherlands

13. Hunt P.B. et al., **1981,** "SCOOT, a traffic responsive method of coordinating signals," Transport and Road Research Laboratory, TRRL laboratory report **1014.**

14. Jacobson, K.L., **1993,** "Transit Signal Priority Treatments in the Puget Sound Region," Pacific Rim Transtech Conference, Seattle.

15. Kay, J.L., et al, **1975,** "Evaluation of First Generation (UTCS/BPS) Control Strategy," Vol 1, Technical Report FHWA-RD-75-27, Washington, DC.

16. Khasnabis, **S.,** et al, **1996,** "NETSIM-Based Approach for Evaluation of Bus Preemption Strategies, Transportation Research Record **# 1554.**

17. Lowrie, P.R., **1982, "** The Sydney Corrdinated Adaptive Traffic System (SCATS)-principles, methodology, algorithms," International Conference on Road on Road Traffic Signalling, London.

18. Mowatt M.G., **1996,** "Transit Signal Priority: a Regional Implementation," Traffic Technology International, October.

19. MUNI, **1987,** "Short Range Transit Plan **1987-1992,**" San Francisco, August **1987.**

20. Nelson, J.T., et al, **1993,** "Approaches to the Provision of Priority for Public Transport at Traffic Signals: A European Perspective," Traffic Engineering & Control **Vol 34(9).**

21. Rowe, S.E., **1987,** "The Los Angeles automated traffic surveillance and control (ATSAC) system," National Conference on Strategies to Alleviate Traffic Congestion.

22. Skabardonis A., **1996,** "Determination of Signal Settings in Systems with Actuated Controllers," Transportation Research Record No. **1554.**

23. Sunkari, S.R., et al, **1995,** "Model to Evaluate the Impacts of Bus Priority at Signalized Intersections," Transportation Research Record No. **1494.**

24. Transportation Research Board, **1994,** "Highway Capacity Manual," Special Report **209,** Washington, D.C.

25. Wallace, C.E., **1992, "TRANSYT-7F** User's Manual," McTrans Center

26. Wood K., R.T. Baker, **1992,** "Using SCOOT Weightings to favor strategic Routes," Traffic Engineering and Control, Vol **33 (6).**

27. Venglar, S.P., et al, **1995,** "Validation of Simulation Software for Modelling Light Rail Transit," Transportation Research Record, No. **1494.**

28. Yagar, **S.,** and B. Heydecker, **1989,** "Potential Benefits to Transit in Setting Traffic Signals," Transportation Research Board, Special Report **# 221.**

APPENDIX A. BIBLIOGRAPHY

1. Alameda Contra Costa Transit District, "Bus priority techniques," final report (draft). prepared by: CalTrans, District 04, Highway Operations, San Francisco, 1979.

2. Allen, D. W. "Signal priority for transit vehicles." University of Toronto, York University, 1976. Joint Program in Transportation, Research report no. 34.

3. Astrop AJ Performance of bus priority measures in shepherd's bush TRL report. 140 1995

4 Babey, GM. "Towards an economic warrant for a bus activated traffic signal system: experience with the analysis tool," Transportation forum. Vol. 1-3, 1984.

5. Behnke, **R** W. ATHENA, an advanced public transportation system and an advanced public information system World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. 1995 6.

6 . Bennett, R. Priority for surface public transport International Union of Public Transport International congress. [Technical papers] ; 42d, 1.

7. Bishop, C. M. Transit signal priority : another look Technical papers from ITE's 1990, 1989, and 1988 conferences. Institute of Transportation Engineers, c1990.

8. Bowen, G.T. Active bus priority in SCOOT 7th International Conference on Road Traffic Monitoring and Control, 1994, London, England.

9. Brilon, W Priority for public transit in Germany Journal of advanced transportation. Vol. 28, no. 1 (Winter 1994)

10. Britton, N. Traffic-light priority measures : no easy solutions Light rail and modern tramway. Vol. 56, no. 669 (Sep. 1993)

11. Bronstein, N Napa system moves buses without stranding autos Tech transfer. Oct. 1995

12. Bul D. Bus advance signals - a green light for bus priority? PTRC traffex '93 conference proceedings. Seminar on traffic control: control systems, information and enforcement, april 1993, birmingham

13. Burton, R Bus priority and UTC systems : the PROMPT project 4th Vehicle Navigation and Information Systems Conference 1993, Ottawa, Ont.

14. Burton, **R.** S. Integration of public transport vehicle priority with urban traffic control Advanced transport telematics: proceedings of technical days, Brussels, March 1993. Commission of the European Communities, Directorate General XIII.

15. Burton, **R.** S. The PROMPT project: achievements and field trials World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. 1995. Vol.6.

16. Casey **R** F Advanced public transportation systems : the state of the art : update '96 U.S. Dept. of Transportation, Federal Transit Administration 1996].

17. Casey, **R** F Advanced public transportation systems : evaluation guidelines : final report Washington, DC : Federal Transit Administration [19941.

18. Celniker, ***S*** Trolley priority on signalized arterials in downtown San Diego Transportation research record. No. 1361 (1992)

19. Chandler, M. J. **H.** "Traffic control studies in London : SCOOT and bus detection," Proceedings of Seminar **M** held at the 13th PTRC summer annual meeting, 1985.

20. Chang, G L Adaptive bus-priority control with and without automatic vehicle location systems Washington, D.C. : Transportation Research Board, [1996].

21 Chang, S K Multiple period optimization of bus transit system Transportation research. Vol. 25B, no. ***6*** (Dec. 1991.

22. Chang G L Bus-preemption under adaptive signal control environments. Transportation Research Record. 1494 pp146-154 1995

23. Cheney C N Innovation in bus priority Proceedings of seminar j held at the 22nd PTRC european transport forum, university of warwick, england, September 1994.

24. Cheney C N Keeping buses moving proceedings of seminar d held at the PTRC european transport,highways and planning 20th summer annual meeting, September 1992), umist

25. Chicago Transit Authority, Automatic vehicle location/control and traffic signal preemption: lessons from Europe Chicago, Ill. 1992.

26. Cisco B A Techniques to assess delay and queue length consequences of bus preemption. Transportation Research Record. 1995. (1494) ppl67-175

27. Cleveland, D.E. "Transit Action Performance Model (TAPM)," Urban Mass Transportation Administration, Office of Technical Assistance, 1986.

28. Cornwell, P. R. "Tram priority in SCATS," Traffic engineering & control. Vol. 27, no. 11, Nov. 1986.

29. Cornwell, P. **R.** "Dynamic signal co-ordination and public transport priority," 2nd International Conference on Road Traffic Control, London, 15-18 April 1986.

30. Courage, K G. Effect of bus priority systems operation on performance of traffic ignal control equipment on NW 7th Avenue: Report 1-8 UMTA 1978.

31. Courage, K. G. Bus priority system studies using instrumented buses 1976.

32. Cracknell J A Bus priority techniques proceedings of seminar d held at the ptrc european transport, highways and planning 20th summer annual meeting, (September 1992)

33. Crain, J.L The Golden Gate corridor bus priority system : (final report) ; prepared for: Transportation Systems Center. Menlo Park : Crain & Associates, 1975.

34. Dailey, D. J. Demonstration of an Advanced Public Transportation System in the context of an IVHS regional architecture World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. 1995. Vol. 6.

35. Daley, K. F. "Public transport and traffic engineering," 12th Australian Transport Research Forum, Vol. 1, 1987.

36. Daley, Ken F. Public transport and traffic engineering Australian Transport Research Forum. Forum papers. 12th (1987) Vol.1

37. Daniel, **J.** Signal priority for public transit vehicles using advanced traffic control systems: a comparative evaluation of ATSAC, SCATS and SCOOT Graduate student papers on advanced traffic management systems. Texas Transportation Institute, [1992]

38. Davidson, F Priority for public transport using advanced transport telematics 3rd Vehicle Navigation and Information Systems Conference 1992 Oslo, Norway).

39. Department of the Environment, Great Britain. Southampton : a linked system of traffic signals with priority access to the route for buses [1976]. Bus demonstration project summary report ; no. 8.

40. Drancsak, M Advanced public transportation systems : a bibliography with abstracts Washington, D.C. : Federal Transit Administration, [1992].

41. Duncan G Maryland bus priority control system. IMSA Journal. 1993/05. 30(3)

42. Earey, D. A. "Bus priority assessment with TRANSM 8" Pretoria, South Africa, National Institute for Transport and Road Research, 1986.

43. Edwards and Kelcey, inc. "Urban corridor demonstration program, Manhattan CBD - North Jersey Corridor: park-and ride studies, bus priority and traffic control, bus access & egress and mainline & nearby bus stops," Tri-State Regional Planning Commission, 1971.

44. Evans, G. Carmarthen Road, Swansea: bus priority within SCOOT 7th International Conference on Road Traffic Monitoring and Control 1994 London.

45. Farges, J.-L. CELTIC bus priority in Lyon 7th International Conference on Road Traffic Monitoring and Control 1994 London, England

46. Federal Highway Administration. Urban traffic control and bus priority system. Offices of Research and Development Report FHWA-76-183 - 184, 1976.

47. Federal Transit Administration Advanced public transportation systems : project summaries [Washington, D.C.] [1996].

48. Federal Transit Administration, Transit & intelligent transportation systems : Advanced public transportation systems seminar, U.S. Department of Transportation, Washington, D.C.] [1995].

49. Fox, K. Integrated ATT strategies for urban arterials : DRIVE II project PRIMAVERA: Bus priority in SCOOT and SPOT using TIRIS Traffic engineering & control. Vol. 36, no. 6 (June 1995)

50. Fox K. Integrated ATT strategies for urban arterials: drive ii project PRIMAVERA: The dewsbury road experiment. traffic engineering and control. Vil 36(7/8) 1995

51. Franco, F P.T. vehicle journey time prediction techniques : approach and developments in the context of Torino PROMPT test site World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. 1995. Vol. 6.

52. Han, B. Real-time control of traffic with bus and streetcar interactions (6th International Conference on Road Traffic Monitoring and Control. London : 1992.

53. Han, B Real-time signal control for transit mixed with traffic Proceedings of Seminar K held at the PTRC summer annual meeting. Vol. P350 (1991)

54. Held, B Bus priority : a focus on the City of Melbourne : Dept. of Civil Engineering, Monash University, [1990]. Civil engineering working paper 91/T6.

55. Henry, J. J. P.T. priority and PRODYN World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. 1995. Vol. 6.

56 Heunemann G Priority for buses serving central zones International Union of Public Transport. 50th International Congress 1993 : Sydney, N.S.W.

57. Heydecker, B.G. "Delay at a junction where there is priority for buses," Proceedings of the Ninth International Symposium on Transportation and Traffic Theory, Delft, the Netherlands, 11-13 July 1984.

58. Hounsell, N. B. Bus priority by selective detection Transport and Road Research Laboratory, 1988. Contractor report 88.

59. Hounsell, N. B. Bus priority : techniques and evaluation 18th PTRC Meeting, Seminar D. Public transport planning and operations. London : 1990.

60. Hounsell, N. B. Protecting buses from congestion using traffic signal control Colloquium on Urban Congestion Management London, 1995.

61. Hounsell N B PROMPT: Priority and informatics in public transport proceedings of seminar h held at the european transport,highways and planning 21st summer annual meeting (September 1993), umist. Volume p370. 1993.

62. Hounsell N.B. Bus priority in SCOOT: results of the PROMPT trials in London. Proceedings of seminar G held at the 23rd ptrc european transport forum, university of warwick, September 1995.

63. Hunter-Zaworski, K M. Bus priority at traffic signals in Portland : the Powell Boulevard pilot project Transportation research record. No. 1503 (July 1995)

64 Jacobson, K L. Transit signal priority treatments in the Puget Sound Region Proceedings, Pacific Rim TransTech Conference (1993 : Seattle, Wash.

65. Jacobson, J. "Analytical model of traffic delays under bus signal preemption: theory and application," 1980.

66. Jenkins, R. P. "Selective detection assessment," South Kensington London, Dept. of Transport, 1981.

67. JHK Assoc "Transit priority feasibility study for Grand Rapids Area Transit Authority," for Grand Rapids Area Transit Authority, 1979.

68. Johnson, R Opticom priority control system Traffic technology international. 1995

69. Kay, J.L. et al, "Evaluation of First Generation (UTCS/BPS) Control Strategy," Vol 1 Technical Report, FHWA-RD-75-27, Final Report, February 1975.

70. Khasnabis, S Signal preemption as a priority treatment tool for transit demand management 2nd Vehicle Navigation and Information Systems Conference, 1991.

71. Khasnabis, S Evaluation of the operating cost consequences of signal preemption as an IVHS strategy Transportation research record. No. 1390 (1993)

72. Kasnabis A. A comparative analysis of two methods to assess operational traffic consequences of bus preemption. Proceedings ITS America Annual Meeting 1995

73 Khattak A Advanced public transportation systems : a taxonomy and commercial availability Institute of Transportation Studies,U niversity of California Berkeley, PATH research report ; UCB-ITS-PRR-93-9, 1993

74. Kochevar-R bus priority treatments in the denver metro area. ITE Compendium of Technical Papers. 1988

75. Koffman, D. "Bus pre-emption of traffic signals in three Santa Clara County corridors," prepared for Santa Clara County Transportation Agency by Crain & Assoc. 1983.

76. Laurens, B Experiences in public transport priority at intersection[s] : centralized versus decentralised approach World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. 1995. Vol. 6.

77. Lee Y C Moving melbourne's traffic with the scram system. proceedings, sixth conference, road engineering association of asia and australasia, march, 1990,

78. Liedtke, G. "Priority service at traffic signals for light-rail-transit and bus," 1st Canadian-German Workshop on Urban Transit Technology Toronto, 1986.

79. Lin G S Adaptive control of transit operations Federal Transit Administration, 1995.

80. Los Angeles Department of Transportation,"Ventura Bus Proirity Traffic Signal Pre-emptoion Demonstration Project, " Los Angeles, 1990.

81. Ludwick, J S. Simulation of an unconditional preemption bus priority system Mitre Corporation [Report] no. MTP-400.

82. Mansfield R S The use of att applications for public transport in SCOPE cities proceedings of the first world congress on applications of transport telematics and intelligent vehicle-highway systems, Paris Volume6. November 1994

83. McGinley, F. J. "The design of tram priority at traffic signals," Journal of advanced transportation, Vol. 19, no. 2, Summer 1985.

84. McGinley, F. J. "Active Tram Priority in Coordinated Signal Systems," Australian Road Research 13 (3), 1983, 173-184

85. Meekums R. The PROMPT project : an overview Colloquium on Urban Congestion Management London, England. 1995.

86. Mechtel, G. H. Architecture requirements for combining Advanced Traveler Information Systems and Advanced Public Transportation Systems proceedings of the 4th annual meeting of IVHS America. Vol. 1. Washington, D.C. 1994.

87. Middelham F the implementation of scoot in the city of nijmegen in the netherlands 7th international conference on road traffic monitoring and control, april 1994.

88. Miser, A. R. Priority roadway ensurement for the efficient movement of public transit systems on Almaden Expressway between Koch Lane and Via Valiente evaluation report Santa Clara, 1979.

89. NATO Committee on the Challenges of Modern Society Bus priority systems / Transport and Road Research Laboratory, 1976.

90 Nelson J.D. Approaches to the provision of priority for public transport at traffic signals: a European perspective Traffic engineering & control. Vol. 34 (9) 1993

91. New Orleans. Office of Transit Administration. "Traffic signal preemption for buses," city of New Orleans in cooperation with JHK & Assoc, 1980.

92. New York City Department of City Planning Improving the efficiency of bus priority treatments : final report 1992.

93. Oakes J A Innovative bus priority measures proceedings of seminar j held at the 22nd PTRC european transport forum, university of warwick, england, September 1994.

94. Ontario Ministry of Transportation and Communications Guidelines for preferential treatment for high occupancy vehicles," Transportation Energy Management Program, Ontario , 1981.

95. Pawley, A. J. R. "Automatic systems for vehicle location, traffic signal priority and passenger information," International Conference on the Bus '86. London, 1986.

96. Pavis A, Congestion management through bus metering at the lincoln tunnel. Transportation Research Record. 1995. (1496) pp35-40 1995

97. Petersen L Implementation of ivhs technologies under brisbane's linked intersection signal system - BLISS. Proceedings of the IVHS AMERICA 1994 Annual Meeting. Atlanta, Georgia. 1994.

98. Piper J, and **R.R.** Cornwell, "Design for Publioc Transport, in Traffic Engineering Practice, **1984.**

99. Presby, **R** Traffic signal preemption for bus priority : annotated bibliography San Francisco : JHK **&** Associates, **1979.**

100. "Priority rules of the road for public transit vehicles.," Ottawa, Roads and Transportation Association of Canada, **1986.**

101 Rankin, W.W. "Traffic control and regulation at transit stops ," Transportation Research Board, National Research Council, **1986.** Synthesis of transit practice **11.**

102 Robbins, G. "Transit preferential streets program: program accomplishments, **1985-1988,**" San Francisco, **1989.**

103. Robertson, D. **I.** Bus priority in a network of fixed-time signals Transport and Road Research Laboratory, TRRL report **LR 666. 1975.**

104. Roberts M Bus priority - the south and west london demonstration project proceedings of seminar c held at the PTRC european transport, highways and lanning **21st** summer annual meeting (September **1993).**

105. Rouphail, N.M. "Operational evaluation of bus priority strategies," paper presented at the **64th** TRB Annual Meeting, **1984.**

106. Seward, S.R, and R.N. Taube, "Methodology for Evaluating Bus-Actuated Signal Preemption Systems, "Transpotration Research Record **#630, 1977.**

107. Slinnn N Bus priority in london and birmingham proceedings of seminar c held at the PTRC european transport, highways and planning 21st summer annual meeting (September **1993**

108. Smith, M J.Evaluation of control strategies for bus preemption of traffic signals Trenton, NJ : New Jersey Dept. of Transportation, **[1985].**

109. Smith, **B.** T. "Improving transit through traffic management," ITE journal. Vol. **57,** no. **9** (Sept. **1987)**

110. Sparmann, J M. Feasibility study of a priority lane network Advanced transport telematics: proceedings of technical days, Brussels, **8-9-10** March **1993.** : Commission of the European Communities, Directorate General XIII, Vol. 2.

111. Sunkari S **R** Model to evaluate the impacts of bus priority on signalized intersections Transportation research record. No. **1494** (July **1995)**

112. Taylor, W C.Bus preemption signal (BPS) : an application of an Advanced Public Transportation System (APTS) Center for Truck Transportation Research, [19951.

113. Thompson A Prioritising bus priority proceedings of seminar c held at the PTRC european transport, highway sand planning 21st summer annual meeting (September 1993)

114. TJKM Evaluation of bus priority signal system : City of Concord 1978.

115. Transportation Research Board, National Conference on Advanced Technologies in Public Transportation, San Francisco, Calif., August 1992, Washington, D.C. : Transportation research circular no. 410.

116. Transport Research Laboratory Bus priority measures (1988-1993) : a selection of abstracts added to the TRL Library Current topics in transport ; no. 19. 1993.

117. Travers Assoc, Bus priority study : Wisconsin Avenue corridor, Montgomery County, Maryland phase 2 / Maryland Department of Transportation, 1976.

118. University of Tennessee, Transportation Center Second National Forum for Advanced Public Transportation (APTS) : new thinking in transit management concepts : Denver Colorado, August 1995

119. Urban Mass Transportation Administration, Advanced public transportation systems : the state of the art : component of Departmental IVHS initiative. U.S. Dept. of Transportation, [1991].

120. Urbitran Assoc., Bus priority improvement study : analysis of bus priority proposals New York, N.Y. [19861.

121 Wilbur Smith Express bus priority concepts, Midtown and Lower Manhattan prepared for New York City Transportation Administration. [1976].

122. Wilbur Smith & Assoc. "On-street transit priority treatments: San Francisco Muni transportation planning, operations and marketing," prepared for San Francisco Municipal Railway, 1976.

123. Webster, **F. V.** Priority to buses as part of traffic management Transport Research Laboratory, TRRL report ; **LR** 448, 1972

124. Williams, T Impact of second priority signal preemption on Kitsap Transit and Bremerton travelers : Transportation Northwest, Dept. of Civil Engineering, University of Washington, [1993].

125. Wood, **K.** Survey of bus priority at traffic light signals in Woking Transport and Road Research Laboratory Supplementary report ; no. 228 UC. 1976

126. Yagar, S. Procedure for real-time signal control that considers transit interference and priority Transportation research. Vol. 28B, n0.4 (Aug. 1994)

127. Yagar, S Real-time signal control for mixed traffic and transit based on priority rules : 6th Engineering Foundation Conference on Issues and Techniques in Traffic Management Palm Coast, Fla. 1991.

128. Yagar, S. "Accomodating transit in TRANSYT," paper presented at the 68th TRB Annual meeting, 1988.

129. Yagar, S. Efficient transit priority at intersections Transportation research record. No. 1390 (1993)

130. Yagar, S., Potential benefits to transit in setting traffic signals, TRB Special report No. 221 (1989)

131. Yagar, S. Improving traffic signal performance and productivity with IVHS: Transportation Association of Canada. Conference. Vol. 4 (1992)

132. Yee, C. "City of Yonkers bus priority feasibility study," final report Traffic Engineering Division, Yonkers, N.Y. 1981.

133. Zurich, pioneer approach to traffic control. Public transport international. Vol. 39, no. 3 (Oct.-Dec. 1990)