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Control Strategies for Transit Priority

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Control strategies for transit priority have long been recognized as having the potential to improve traffic performance for transit vehicles, which could also lead to improved schedule reliability, reduced operating costs, and greater ridership. However, there have been relatively few successful implementations of transit priority measures on urban networks with signalized intersections in coordinated signal systems. Existing control strategies are reviewed, the major factors affecting transit priority are identified, and the formulation of both passive and active transit priority strategies for arterials with coordinated traffic signals are described. The proposed strategies were evaluated on a real-life arterial corridor. The proposed passive and active priority strategies placed major emphasis on the systemwide improvements to the transit movements and on minimization of the adverse impacts to the rest of the traffic stream. The criteria used to grant priority include the availability of spare green time in the system cycle length, progression at the downstream intersection(s), and schedule adherence. An evaluation technique was also developed to assist in the design of the signal priority strategies and to predict the impacts of the transit priority measures.

There is an increasing emphasis on efficient transit operations and strategies for transit priority. A number of transit agencies are implementing integrated automatic transit vehicle location and monitoring systems to better monitor transit operations and implement various measures to improve transit performance. FTA has initiated the Bus Rapid Transit program, which involves the development and demonstration of improved transit operations in several areas nationwide (*1*). Several efforts are under way to develop transit signal priority strategies that take advantage of the recent developments in signal controller technology and communications and surveillance systems (*2*).

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This paper summarizes the methodology and findings of a research study conducted to develop and evaluate strategies that could be used to provide priority to transit in urban networks (*3*). Transit for the purposes of this study is defined as buses (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 strategies 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 strategies?

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BACKGROUND

Transit priority measures fall into two major categories: those that are based on facility design and those that rely on traffic control. Transit priority measures based on facility design usually consist of exclusive lanes for transit on arterials, as well as street designs that facilitate transit movements. Examples include bus bays and bus bulbs (widened sidewalks at bus stops) to facilitate safe loading and reduce conflicts with other vehicles and on-street parking management to ensure the availability of adequate curb space for buses. The effectiveness of such measures is largely site specific. For example, bus bulbs can work well if there is sufficient road capacity for the traffic to pass the stopped bus, but they can contribute to long queues and delays if the bus blocks traffic.

Priority measures that rely on traffic control range from changes to fixed-time signal settings so that they favor transit, signal preemption at specific intersections, and systemwide priority based on integrated automatic transit vehicle location and monitoring systems and real-time traffic control systems.

Traffic signals along arterials and networks operate in coordination to provide for progression of the major through movements. Most of the systems operate with signal timing plans prepared offline on the basis of historical data. Transit priority is provided in offline systems by determining the signal settings (cycle length, green times, and offsets) that favor bus movements. Figure 1 shows the trajectories of both a vehicle platoon and a bus. Bus priority could be provided by adjusting the offset between the two signals to account for the slower speed of the bus and the midblock dwell time. Often, bus stop locations must be alternated (if possible) between the nearside and farside at successive intersections, so the buses would not have to stop at both the stop line (when the signal is red) and the bus stop.

Signal preemption may hold the green until the bus clears the intersection (phase extension) or advance the start of the green for the phase serving the buses (phase advance). Other options may include a bus-activated exclusive signal phase and skipping of a nontransit-serving phase(s). Signal preemption is usually implemented by using strobe light emitters on the transit vehicles and special light detectors at the signal, radio control, or special loop detectors that recognize bus signatures. Signal preemption has been widely applied at isolated signals and for light rail, but several operating agencies have resisted the implementation of bus preemption in coordinated systems because of the potential adverse impacts to the rest of the traffic stream. Phase skipping or red truncation could cause confusion to the motorist, loss of coordination, and long delays to the traffic stream. Also, for nearside bus stops preemption through driver control is usually 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 buses running ahead of schedule.

A number of "online" signal control systems are operational; these update the timing plans in real time on the basis of data from detectors. Such systems provide signal priority at the local or the systems

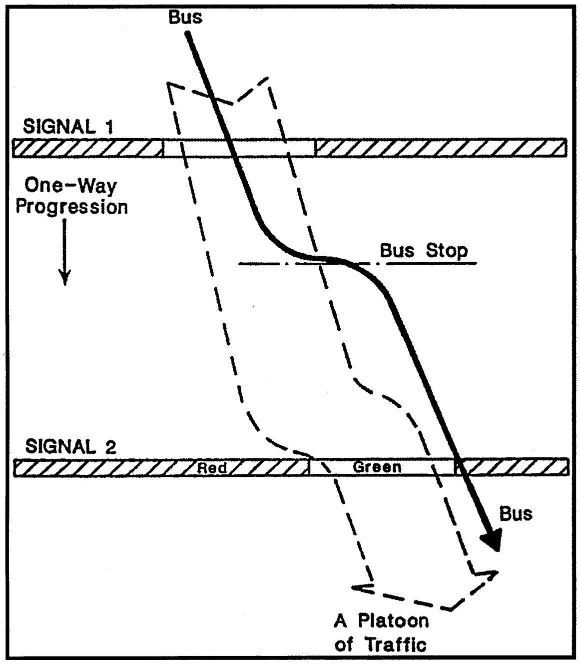

FIGURE 1 Transit and automobile vehicle trajectories.

level. The SCATS (Sydney Coordinated Adaptive Traffic System) (*4*) transit priority logic includes green extension, special phase sequences, and compensation to the nontransit phases. The SCOOT (Split Cycle Offset Optimization Routine) system (*5*) grants priority to buses (phase extension and recall) on the basis of a user-specified degree of intersection saturation to avoid excessive delays to the rest of the traffic. Field evaluations in London showed bus delay savings that ranged from 5 to 10 s/signal with no disbenefits to the rest of the traffic. The UTOPIA system in Turin, Italy (*6*), is an adaptive control system that provides absolute priority to transit by continually optimizing the signal settings over a short time interval (rolling horizon). Reported benefits include a 20 percent increase in the average bus speeds without disbenefits to the rest of the traffic. There are no operational real-time control systems in the United States with transit priority. Currently, improved algorithms for signal priority are being developed as part of a Transit Cooperative Research Program (TCRP) research project (*7*).

DEVELOPMENT AND EVALUATION OF TRANSIT PRIORITY STRATEGIES

The choice of the types of transit priority treatments to be used, the way(s) in which they should be deployed, and their effectiveness depend on several factors, including

- Network configuration and characteristics: single arterial, grid network, signal spacing, number of lanes, and pedestrian presence (e.g., in downtown areas), that is, the 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, and level of congestion, that is, the extent to which traffic congestion interferes with bus operations and the nature of the interference.
- Frequency and 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 and 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 this study. Emphasis was placed on the development of transit priority algorithms for buses traveling along arterials. It was assumed that there are no transit vehicles on the cross streets. Transit priority strategies become very complicated if there are conflicting bus movements at an intersection. In this case one should determine the type of priority over the automobile traffic, as well as which transit movement receives priority. For example, one may give priority to the buses running late subject to adherence to the schedule on the conflicting transit movements.

The effectiveness of transit priority strategies depends 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 effectiveness of any signal priority measures would be limited. Field observations should be undertaken to quantify the sources and amount of bus delays other than those at traffic signals (passenger loading and unloading, midblock interference) along with proposals for improvement before the development and implementation of transit signal priority.

Development of Passive Priority Strategies

Passive priority strategies consist of methods for the development of signal timing plans (cycle length, green times, and offsets) to favor transit along signalized arterials. This can be accomplished by either manually modifying the background coordinated timing plans on the basis of bus service characteristics (as illustrated in Figure 1) or using a signal timing optimization program (e.g., TRANSYT-7F) (*8*).

TRANSYT-7F is one of the most commonly used models for the optimization of the timing plans for arterials and networks controlled by traffic signals. It simulates the movement of traffic platoons and uses an iterative 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):

$$\mathrm{PI} = \sum_{i=1}^{N} W_{D_i} D_i + K W_{S_i} S_i \qquad (1)$$

where

N = number of links in the system,
W_{D_i} = weighting factor for delay in Link i,
D_i = total delay (vehicle-h) in Link i,
K = the stop penalty (the weight of stops relative to the weight of delay),
W_{S_i} = weighting factor for stops in Link i, and
S_i = number of stops on Link i.

TRANSYT-7F can be used to develop timing plans to favor buses by coding the bus movements as separate links and specifying delay and stops weighting factors (WFs) for the bus links so the signal optimizer would favor the transit vehicles over the rest of the traffic. The choice of WF depends on the bus frequency, traffic patterns, and network characteristics. Figure 2 shows the sensitivity of traffic performance

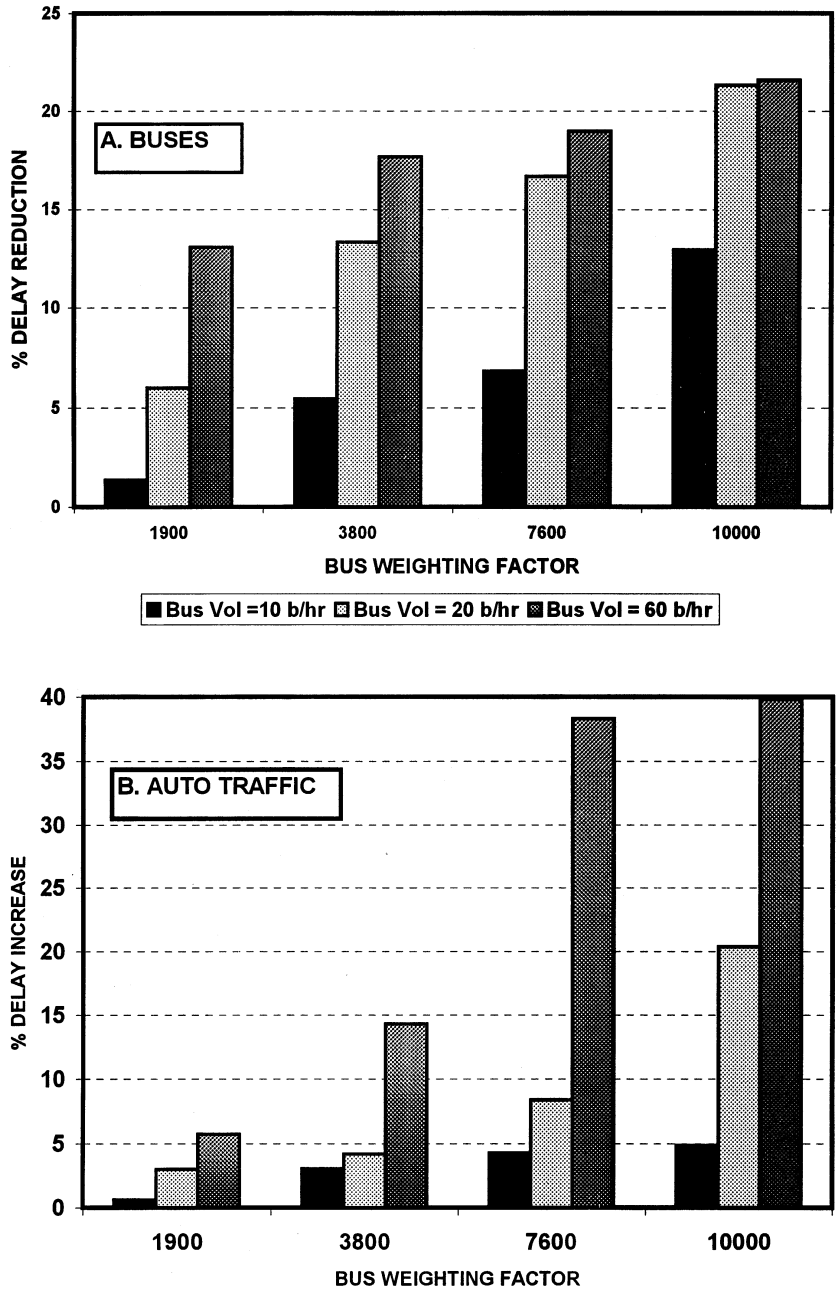

FIGURE 2 Sensitivity of traffic performance to transit-weighted timing plans.

to the WF for a typical arterial with 10 coordinated signals and the trade-offs involved with a timing plan for transit priority depending on the transit service frequency.

The top portion of Figure 2 shows that for bus volumes of 10 buses/h (6-min headways), the best transit priority settings are obtained for a WF of 10,000 (the maximum value accepted by TRANSYT-7F). The delay to the buses is reduced by 13 percent at a small disbenefit to the rest of the traffic (about a 5 percent increase in delay). For higher bus volumes, high values of WF would result in signal settings that seriously degrade traffic performance for the automobile traffic without additional benefits for the buses.

Fixed-time plans that favor buses are effective for high bus volumes and fairly predictable arrival times at the intersection. For example, uncertainty in bus arrival times at the intersection because of high variability of bus dwell times may substantially reduce the benefits of transit-weighted fixed-time plans.

Formulation of Active Priority Strategies

Active priority strategies involve preemption at specific traffic signals or systemwide adjustments to the signal timing plans on the basis of real-time information on traffic conditions and bus arrivals at the intersection.

The proposed active priority consist of (*a*) criteria for the selection of specific intersections in the system to provide transit priority and (*b*) procedures for minimization of the adverse impacts to the rest of the traffic stream.

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

- Criterion 1: spare green time. Signal preemption may not result in oversaturated movements at the signalized intersection or loss of signal coordination. That 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:

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

where

G_e = the spare green time in the cycle,
N = number of phases,
G_i = green time for Phase *i,* and
X_i = degree of saturation for the critical link moving on Phase *i*.

This criterion guarantees maintenance of the normal phasing sequence at the intersection and coordination along the arterial. Thus, the proposed preemption strategy should not be confused with the signal preemption for emergency vehicles that interrupt the normal timing sequence to provide service as soon as possible, subject to safety constraints.

- Criterion 2: bus route progression. The decision to grant priority at an intersection should consider the bus arrival times at the downstream intersection(s). For example, advancing the green time at the upstream signal may result in an additional bus delay downstream, thus achieving no net delay benefit for the bus. Figure 3 shows an example of "wasted" bus preemption at Intersection 1. Because the bus must stop at Signal 2 downstream, the bus delay is the same as that in the case of no preemption. Therefore, the signal settings at the adjacent intersections should be adjusted to account for the preemption effects. This could be difficult to be implemented in offline control systems with fixed-time plans unless buses arrive almost on each cycle. However, online control systems (such as SCOOT) should be able to make systemwide changes in the timing plans.
- Criterion 3: schedule adherence. Transit priority should not be provided if the result is that buses may be ahead of schedule, and some proposed strategies provide priority only to those buses that are behind schedule. However, favoring a "late-running" 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 automatic vehicle location systems to allow real-time determination of location and status.

The criteria presented above would also prevent bus signal priority from causing adverse effects on the traffic stream. Other procedures suggested in the literature included (*a*) inhibition (i.e., limit the frequency of preemption by transit vehicles) and (*b*) compensation [i.e., provide more green time to the nonpriority traffic movements in the signal cycle(s) after the preemption]. The inhibition function may not be required because priority would be given only to selected buses (those that are behind schedule). 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 nonpriority phase(s) would create large queues and delays to the through traffic.

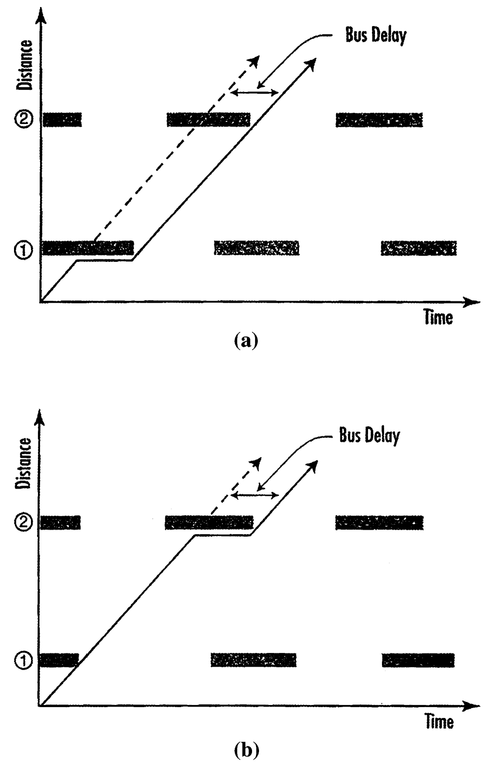

FIGURE 3 "Wasted" active signal priority at Intersection 1: (*a*) no preemption; (*b*) bus preemption.

Analysis Techniques

There is a need for laboratory planning, design, and evaluation of proposed transit priority strategies before field implementation. However, analytical models that predict the impacts of bus priority apply only to isolated signalized intersections (*9*). Several simulation models can model transit operations in coordinated systems and predict performance measures [measures of effectiveness (MOEs)] separately for automobiles and buses (TRANSYT-7F, CORSIM, and VISSIM) that can potentially be applied to assess transit priority strategies.

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. Also, it assumes constant dwell times and cannot realistically model bus movements at bus stops near the intersection stop line.

The CORSIM microscopic simulation model (*10*) developed for FHWA simulates in detail individual vehicles and transit operations and various control strategies that range from fixed-time signals to traffic-responsive control. The standard version of the model can explicitly simulate signal priority for transit vehicles on exclusive lanes (buses and light rail vehicles traveling on exclusive lanes parallel to the automobile traffic with interactions only at the intersection stop line), but it cannot explicitly model signal preemption for buses sharing the roadway with automobiles. One possible approach is to apply alternate fixed-time plans in successive time periods: one plan for normal signal operation and another plan that simulates the priority settings at selected signals (*11*). This approach is tedious and time-consuming and cannot test the effects of various control parameters (e.g., detector location and extension interval) because fixed-time plans are used to emulate preemption. The latest version of CORSIM provides an interface with signal controllers to test alternative real-time control strategies including signal priority, but it is not widely available.

VISSIM is a microscopic model developed in Germany (*12*). The model can explicitly model several options for signal priority for buses sharing the roadway with automobiles and has been applied extensively in Europe. There have been no documented applications of the model in the United States. Currently, the model is being applied by King County Metro in the state of Washington to develop transit priority strategies in Seattle and in the TCRP A-16 project to evaluate transit priority algorithms (*7*). The findings from those applications would provide valuable information on the capabilities and limitations of VISSIM for U.S. conditions.

Development of Analysis and Evaluation Procedure

A new procedure was developed in this study to evaluate the proposed active priority strategies. This technique is based on the widely used TRANSYT-7F model. The technique does not involve any software development; it uses several of the advanced features of the TRANSYT-7F model in successive model runs. The procedure consists of the following steps (Figure 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 of traffic performance.
2. Select intersections for signal priority. Examine the flow-profile output by the TRANSYT-7F model to determine the bus arrival times in the signal cycle. If the bus is delayed, determine if spare green time is available to grant the bus priority. The spare green time is calculated from Equation 2 by using the degrees of saturation and green times for the critical links moving on each phase shown in the TRANSYT-7F model output.
3. Reoptimize the signal timing plans for absolute priority to the buses at the intersections selected in Step 2. Import the optimal timing plans developed in Step 1. Specify weighting factors of zero for the automobile links and the highest allowable value (10,000) for the bus links (model Record Types 37/38). The TRANSYT-7F optimizer would then determine the signal settings for minimum delay and stops on the bus links by ignoring the traffic performance of the rest of the traffic stream. Optimize the splits and offsets only for the intersections identified in Step 2 and keep the signal settings for the rest of the intersections fixed (by coding the intersection number as negative on Record Type 1X).
4. Code the changes in the signal settings from Step 3 into the basic TRANSYT-7F file and perform a simulation run to predict the traffic performance. The output from this TRANSYT-7F run represents the traffic performance under bus priority conditions.
5. Calculate the MOEs for the traffic stream in the analysis period as the weighted average of the MOEs for the signal cycles with and without signal priority. For example, by assuming that the bus headway is 6 min and the cycle length is 90 s, a bus would arrive about every four signal cycles, or about 10 percent of the cycles in 1 h would include bus arrivals. The combined traffic performance would be

$$\text{MOE} = a\text{MOE}_p + (1 - a)\text{MOE}_{np} \tag{3}$$

where

MOE = predicted performance measure (e.g., travel time, delay, and stops),
a = proportion of signal cycles in the analysis period with bus arrivals,
MOE_p = predicted performance measure with bus priority (Step 5), and
MOE_{np} = predicted performance measure without bus priority (Step 1).

This simple procedure can be used to design and evaluate a bus priority strategy along signalized arterials and networks. Comparisons with CORSIM simulations indicate that it provides comparable results in much less time and with much less effort. This technique can also be used to assess traffic-responsive control strategies that are based on updating of fixed-time plans. For example, the SCOOT control logic can be modeled as a series of optimal timing plans per each time interval without signal transition.

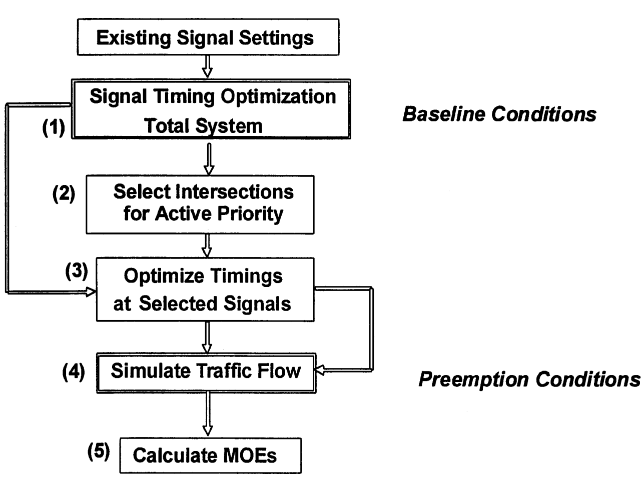

FIGURE 4 Proposed evaluation procedure.

APPLICATION AND ASSESSMENT OF PROPOSED STRATEGIES

A segment of San Pablo Avenue, a major urban-suburban arterial in the San Francisco Bay Area, has been selected as the test site for evaluation of the proposed strategies. San Pablo Avenue serves as an alternate route to the I-80 freeway during the peak periods and also carries a significant number of local and express buses. The test segment is 6.7 km (4.2 mi) long and includes 21 signalized intersections. Throughout the arterial there are four travel lanes plus turning bays on each intersection approach. Table 1 includes basic information on the test arterial characteristics.

Basic data on the study area and information on transit service were assembled and verified through field checks. The data were coded into the TRANSYT-7F and CORSIM simulation models. Comparisons of simulation runs with field measurements on critical intersections along the study segment indicate that the models reasonably represent existing operating conditions.

The proposed transit priority strategies were applied on the study corridor, and their effects (travel time, delays, and stops) were evaluated through simulation separately for the transit vehicles and the rest of the traffic stream. The baseline conditions for the study area were coordinated signal operation with optimal timing plans for the

TABLE 1 Signalized Intersections Along San Pablo Avenue 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		Alcatraz	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	8
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

1 ft = .3 m

prevailing traffic patterns. It should be noted that several previous studies compared the effectiveness of transit priority against old coordinated timing plans or isolated signal operation. Such comparisons tend to mask the true effects of any transit priority scenario because the improvements may be due to the changes in traffic control that also benefit the transit vehicles.

Optimal timing plans that favor buses along the arterial reduced the delay to buses by 14 percent, reduced the number of stops by 1 percent, and improved the average bus speed by about 4 percent. This translates into delay savings of about 2 s/bus/intersection. The impacts on the rest of the traffic stream were marginal (1 percent increase in total delay). Most of the increase in delay 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 buses/h (6-min headways) and average dwell times of 16 s. Sensitivity analyses were performed by assuming different bus frequencies and dwell times. The simulation results showed that the estimated transit improvements are insensitive to a range of bus volumes of up to 30 buses/h.

The evaluation of bus preemption at specific signals with offline fixed-time timing plans showed that delay savings of up to 6 s/intersection/bus could be achieved. Over the study area, the bus travel time savings from signal priority at the selected intersections would be about 2 min. The effects on the rest of the traffic stream were insignificant. Sensitivity analyses indicate that the benefits would be higher with higher bus frequencies.

The active priority strategies tested were based on the criterion of spare green time to maintain coordination and minimize the adverse effects on the rest of the traffic stream. Greater benefits would result if active priority was used at intersections for buses that are experiencing delays. Tests of this approach showed that it produced excessive queues on several side streets, and it appeared to discharge buses and other vehicles from the front of one queue at the upstream intersection only to deliver them to the back of the queue downstream. Such an approach is not likely to be implementable in the study corridor or in any real-life system.

Exploratory analyses of systemwide transit priority based on online signal control plus automatic transit vehicle location and monitoring technologies added to transit showed modest improvements over preemption with fixed-time plans. However, these results are conservative because the evaluation technique used (or any other existing model) cannot explicitly simulate the performance of real-time systems.

CONCLUSIONS

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 that facilitate transit movements and transit-weighted signal settings, are generally low-cost, easily implementable measures that are effective in simple network configurations, systems with high bus frequencies, and systems with 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. The proposed passive and active priority strategies developed in this study placed major emphasis on the systemwide improvements to the transit movements (as opposed to a single intersection) and on minimization of the adverse effects on the rest of the traffic stream.

Existing simulation models cannot explicitly model most of the active preemption strategies. In this study a simple evaluation technique that can produce results similar to those achieved with other simulation models but in much less time and with much less effort was developed. 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 for the transit vehicles. Passive priority strategies improved bus delay by 14 percent, and active signal priority reduced the delay by up to 6 s/intersection/bus without adverse effects on the automobile traffic. These results apply to a specific site and could be better on routes with higher bus frequencies.

Improved capabilities in traffic control and transit systems offer considerable potential in the development of effective control strategies for transit that outperform the existing signal priority techniques. There is a need to develop improved algorithms to take advantage of such technological advancements, comprehensive simulation tools for thorough laboratory evaluation of proposed strategies, and field demonstrations. A comprehensive research program has been initiated at the Partners for Advanced Highways and Transit (PATH) Program of the University of California at Berkeley to develop adaptive signal priority algorithms and modeling tools (*13*). The proposed algorithms and models will be demonstrated in the field and evaluated as part of the Santa Clara County Valley Transportation Authority's participation in FTA's Bus Rapid Transit demonstration program.

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