Bus-Preemption Under Adaptive Signal Control Environments

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To explore the advantages of integrating bus preemption and adaptive signal control, an integrated model for adaptive bus-preemption control in the absence of automated vehicle location systems was developed. In the proposed system, unconditional priority is not given to buses over passenger cars. Instead of using pre-specified strategies such as phase extension, phase early start, or special bus phase, preemption decision is based on a performance index, which includes vehicle delay, bus schedule delay, and passenger delay. An extensive simulation evaluation with respect to the integration of adaptive control with preemption is also presented. The developed model displays promising results.

Finding ways to relieve traffic congestion has long been a priority of transportation and traffic engineers. While advanced traffic management systems (ATMS) and advanced traveler information systems (ATIS) have alleviated some of the problems, these methods alone are not enough. New approaches are vital as the demand on transit systems continues to grow. Hence, to substantially improve urban traffic conditions, effective strategies are needed from both demand and supply sides. Preferential treatment for buses such as signal preemption, devised to encourage the use of public transit systems, is one of the latest demand-side strategies for relieving urban congestion. Since adaptive signal control is one of the latest supply-side methods for relieving urban traffic congestion, integrating the two methods is essential.

Over the past several decades, several studies related to bus-preemption strategies have been conducted, involving experimental testings (*1–11*) and analytical explorations (*12–15*). Some of the transit preemption methods have been implemented in the existing signal systems, such as UTCS/BPS (*16*), UTOPIA (*17*), SCRAM (*18*), and SPPORT (*19,20*). Overall, the potential benefits of properly designed and implemented bus-preemption strategies have been well-justified in these studies.

Because preemption strategies traditionally favor bus users over passenger-car drivers, their implementation is a sensitive issue and has often prompted debate. Therefore, a rigorous evaluation of the trade-offs and complex interactions between transit users and passenger-car users under various traffic conditions is necessary before any strategy can be successfully developed and applied. Although a review of the literature shows that considerable progress has been made, future research should address the following issues:

- Integration of bus preemption with adaptive signal control to ensure that the optimal signal control minimizes not only vehicle delay, but also passenger delay. Most existing studies on bus preemption, with the exception of UTOPIA (*17*), did not operate under acyclic adaptive signal control systems.
- Evaluation of the bus-preemption need from transit system management perspectives. For instance, in comparing the trade-offs between competing signal plans, the status of an approaching bus, either ahead of or behind its schedule, should be considered, along with its loading factors.
- Incorporation of information from automated vehicle location (AVL) systems in the design of bus preemption and adaptive signal control.

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In this study, the first two issues are discussed with an integrated adaptive system for bus-preemption and signal control. The incorporation of AVL information and its impact on the systems effectiveness will be presented elsewhere (Chang et al., unpublished data). This discussion includes:

1. A description of the proposed adaptive preemption system for intersection control, along with its principal modules and their interrelations.
2. A detailed presentation of the logic and mathematical formulations for each primary system module.
3. An experimental plan for assessing the effectiveness of the proposed system under various traffic conditions, and the results of evaluation.

AN INTEGRATED SYSTEM FOR BUS PREEMPTION AND ADAPTIVE SIGNAL CONTROL

To execute bus preemption effectively in an adaptive signal control environment, the control algorithm should:

- Incorporate bus preemption as one of the adaptive signal control functions;
- Use an adaptive control logic with real-time algorithms instead of using pre-specified strategies, such as phase extension, phase early start, or a special bus phase;
- Impose a minimum green constraint and automatically update it after every switchover decision, based on the existing traffic conditions and driver safety; and
- Have a performance function for system evaluation, based on the current queue length, bus loading factors, and bus schedule delay.

Figure 1 presents the relationship between all principal components of the proposed integrated system, including the bus-preemption module and other local adaptive control components. The integration of these modules enables the system to provide a preventive adaptive control every 3 sec based on the detected real-time

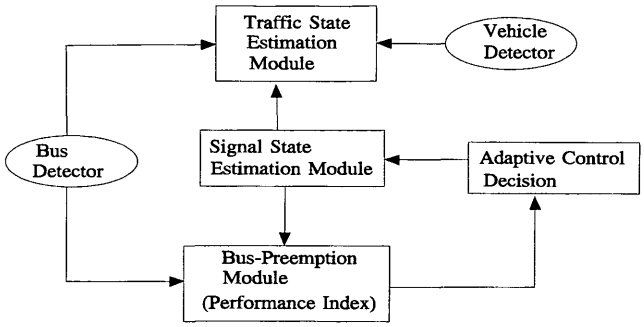

FIGURE 1 The relationship between principal modules of the proposed adaptive control system with bus preemption.

demand. The interaction between the local optimization module and the bus-preemption module will allow the system to operate under both, with and without bus arrival conditions.

In the operating process, shown in Figure 2, the real-time arrival information is provided by detectors for both private vehicles and buses, and is used to estimate the arrival and discharge of flows and the queue lengths at the current time step (in the traffic state estimation module) based on the existing signal state. The estimated traffic state is used to determine the optimal adaptive control strategy with the detected traffic conditions. If any bus has been identified by the surveillance system, then the benefit of offering bus-preemption status is evaluated while making a control decision. The resulting decision is used to calculate the signal state elements in the signal state estimation module for the succeeding time step. The major function of each module is described in the next section.

The proposed adaptive signal control module does not rely on prediction models for arriving traffic over the entire time horizon, and thus is myopic in nature. A modified version of an integrated system that uses AVL information and a neural network model for prediction has been presented elsewhere (Chang et al., unpublished data). The notations used in this discussion are given in Table 1.

Surveillance Systems

The operation of the adaptive control system requires:

- Vehicle detectors placed at the location of 36.6 m (120 ft) per lane from the stop line for estimating queue length and 15.25 m (50 ft) per lane from the upstream intersection for estimating the arrivals when the downstream detectors are occupied; and
- Bus detectors placed at the location of 36.6 m (120 ft) per lane from the stop line for reducing the uncertainty of a bus arrival due to additional delay in loading/unloading, lane-changing behaviors, curb parking or turning movements; and the stop line (per lane) for detecting bus departures.

Traffic State Estimation Module

The estimation of traffic conditions for signal optimization or bus preemption involves determining (*a*) current queue length, (*b*) expected demand, and (*c*) anticipated discharged flow. Computation of queue length is vital for the execution of the bus-preemption function. It is one of the key factors in making a signal control decision, as it is critical in determining the allowable minimum green duration. Hence, in this module, data supplied by the detectors are used to estimate the arrival and discharge of flows, and consequently, the queue lengths for each time step. The estimated queue length is used in the Performance Index (*PI*) module. A simple queue estimation concept, shown in Equation *1*, is used to estimate the short-term queue length at the target intersection.

Queue Length Estimation

$$Q_l^i(k+1) = Max\{Q_l^i(k) + A_l^i(k+1) - d_l^i(k+1), 0\} \quad (1)$$
$$\forall\, l \in P^i;\ \forall\, P^i \in i;\ \forall\, i \in H$$

The queue length at a given time step is computed from (*a*) the queue length of the previous time step, (*b*) the number of new

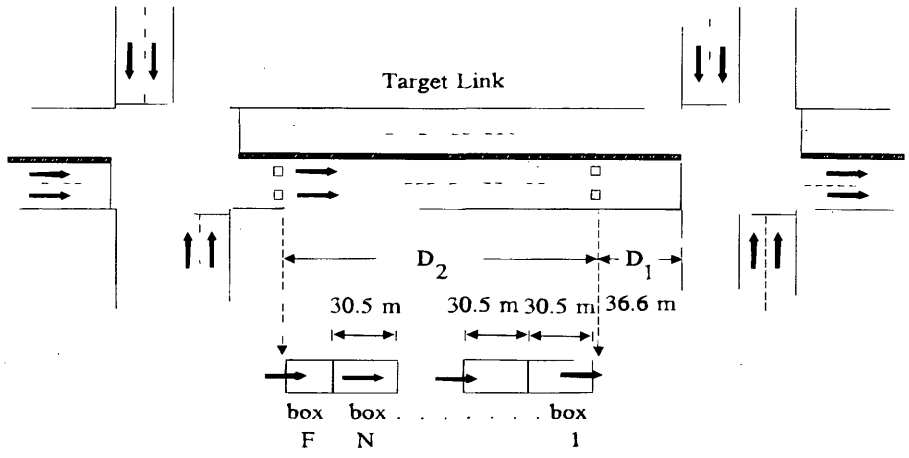

FIGURE 2 The relation between detector placement and arrival estimation.

TABLE 1 Notations Used in the Study

T	:	Duration of a time step (seconds)
H	:	Set of signal phases at the control intersection
P^i	:	Set of lane groups in phase i
$\phi^i(k)$	:	0 if signal state is green for phase i and time step k 1 if signal state is red for phase i and time step k
$\xi^i(k)$	:	1 if existing signal state of phase i is switched at end of time step k 0 otherwise
G^i_{min}	:	Minimum green for phase i (seconds)
G^i_{max}	:	Maximum green for phase i (seconds)
$U^i(k)$	:	Green time used by phase i, at the end of time step k (seconds)
Y^i	:	Yellow time for phase i (seconds)
AR^i	:	All red time for phase i (seconds)
$R^i(k)$	:	Minimum waiting time for a green for phase i (green phase of time step k), if a switchover occurs at the end of time step k
$S^i_{l,g}$	:	Saturation flow rate for green time, for lane l, in phase i
$S^i_{l,g}$	:	Saturation flow rate for yellow time, for lane l, in phase i
q^i_l	:	Given saturation flow rate for lane l
$q_{l,u}(k)$	:	Traffic flow of lane l, detected by upstream detector, u, at time step k, for phase i
$q^i_{l,d}(k)$	:	Traffice flow of lane l, detected by downstream detector, d, at time step k, for phase i
$A^i_l(k)$	:	Number of arrivals in lane l, provided by downstream detectors at time step k, and phase i (vehicles)
$d^i_l(k)$	:	Discharged flow of lane l at time step k, and phase i (vehicles)
$Q^i_l(k)$	:	Estimated queue length of lane l, at time step k, and phase i (vehicles)
D_1	:	Distance between the downstream detector located at 36.6 m (120 ft) and the stop line (m)
D_2	:	Distance between the upstream detector and the downstream detectors (m)
$a^i_{l,1}(k)$	:	Number of arrivals in lane l moving in Box l from the upstream detectors at time step k, for phase i (vehicles) (see Figure 2)
$a^i_{l,N}(k)$	:	Number of arrivals in lane l, moving in box N, fro the upstream detectors at time step k, and phase i (vehicles) (see Figure 2)
N	:	Number of integer boxes from the upstream detectors to the downstream detectors (see Figure 2)
F	:	Fractional part of the box, closest to the upstream detector, which may not be accommodated within D_2 (Figure 2)
L_v	:	Average vehicle length (m)
S_d	:	Distance between the rear of a vehicle and the front of the following stopped vehicle (m)
t^p_{sd}	:	Starting delay for a passenger car (seconds)
t^b_{sd}	:	Starting delay for a bus (seconds)
n_p	:	Average number of passengers in a passenger car
$PQ^i_l(k)$	:	Estimated passenger car queue length of lane l, at time step k, for phase i (vehicles)
$B^i_l(k)$	:	Number of detected buses in lane l, at time step k, and phase i that have not yet cleared the intersection (vehicles)
$P^j_{j,l}(k)$	:	Number of passengers in bus j, in lane l, at time step k, for phase i
$SD^j_{j,l}(k)$	:	Schedule delay of bus j, in lane l, at time step k, and for phase i
$D^j_{j,l}(k)$	:	Total delay of bus j, in lane l, and phase i' (red phase), if green is extended at the end of time step k for the green phase, i
$F^j_{j,l}(k)$	:	Number of vehicles detected ahead of bus j, in lane l, at time step k, and phase i

arrivals, and (c) the discharged flow. However, when the queue length is calculated for a red approach, the discharged flow term in Equation 1 is reduced to zero. The equation is used to determine passenger car and bus queue lengths. $A^i_l(k+1)$ and $d^i_l(k+1)$ are estimated from real-time surveillance data and signal control states.

Estimation of Arrivals

Depending on whether the downstream detectors are occupied by the queued vehicles, the system uses either Equation 2 or Equation 3.

$$A^i_l(k) = q^i_{l,d}(k-1) \text{ if } Q^i_l(k) \leq D_1 \quad (2)$$

$$A^i_l(k) = a^i_{l,1}(k) \text{ if } D_2 \geq Q^i_l(k) \geq D_1 \quad (3)$$

$q^i_{l,d}(k-1)$ is measured in real time from the downstream detectors, while $a^i_{l,1}(k)$ is estimated from the upstream detector information, based on the following modified PRODYN (*21*) concept:

$$a^i_{l,1}(k) = a^i_{l,2}(k-1) \quad (4)$$

$$a^i_{l,(N-1)}(k) = a^i_{l,N}(k-1) + (1-F)\,q^i_{l,u}(k-1) \quad (5)$$

$$a^i_{l,N}(k) = F q^i_{l,u}(k-1) \quad (6)$$

Estimation of Discharged Flows

The discharged flow $d^i_l(k)$ in a control phase i depends on the adaptive control decision and the signal control state (i.e., the green, yellow, and red duration). It can be approximated with the following equation:

$$d^i_l(k) = (1-\phi^i(k))[S^i_{l,g}(1-\xi^i(k)) + S^i_{l,y}\xi^i(k)] + S^i_{l,g}\xi^i(k)\phi^i(k) \quad (7)$$

Depending on the signal state (red or green) and the control decision, the discharged flow becomes equal to the saturation flow rate for green or yellow time. For example, when the signal state is green ($\phi^i(k) = 0$) and the control decision is to switch the green ($\xi^i(k) = 1$), then the discharged flow is equal to the saturation flow rate for yellow.

Signal State Estimation Module

This module monitors the signal state, computes the elapsed green time, and estimates the minimum green duration in real time. The logic for all its functions is given in the next section.

Signal State

The signal state of any phase i, $\phi^i(k)$ at time step k is given by (*21*)

$$\phi^i(k) = \xi^i(k-1) + \phi^i(k-1) - 2\,\xi^i(k-1)\,\phi^i(k-1)\,\forall i \in H \quad (8)$$

The first term represents the control decision at the end of time step $k-1$. The second term signifies the signal state of phase i at time step $k-1$. $\phi^i(k)$ is a binary variable. If the signal state is red for time step $k-1$, (i.e., $\phi^i(k-1)=1$) and the control decision at the end of the time step is to switchover ($\xi^i(k-1)=1$), then the signal state for time step k from Equation 8 must be 0, which corresponds to a green state.

Elapsed Green

The green time already used up by phase i at time step k is computed with the following equation (*21*):

$$U^i(k) = (U^i(k-1) + T)\,(1 - \xi^i(k-1))\ \forall\, i \in H \tag{9}$$

Based on the control decision, $\xi^i(k-1)$, green time is either increased by a duration of T seconds, or it is reduced to zero.

Minimum Green

Minimum green is recommended to be the shortest green time during which drivers can be expected to react safely to signal changes. It also must be sufficiently long for discharging the average waiting queue during each control phase i. A mathematical representation of such a requirement is given as

$$G^i_{\min} = t^p_{sd} + \left(\text{Max}\left\{\left(\frac{D_1}{L_v + S_d} + 1\right), \underset{l}{\text{Avg}}\, Q^i_l(k)\right\}\right)\left(\frac{3{,}600}{q^l_s}\right) \tag{10}$$
$$\forall\, l \in P^i, \forall\, P^i, \forall\, i \in H$$

Thus, the minimum green ($G^i_{\min}$) for phase i is made up of the following components:

- Starting delay, t^p_{sd}, due to switching of signals, and
- The maximum of the two expressions, for safely discharging the average queue length: first denotes the number of vehicles that will occupy the length D_1, and second indicates the average queue length for all lanes in phase i at time step k.

Maximum Green

A sufficiently long green can be set so the control algorithm can effectively handle oversaturated conditions. It also can be set by the user to respond to demand variations during different periods, such as morning peak, evening peak, day off-peak, night off-peak, and holidays.

Bus-Preemption Module

A review of the literature shows that most adaptive control strategies do not consider the delay in the schedule of a bus while making a signal-state decision for bus preemption. Hence, the decision to switchover to another phase or not may not be an optimal solution. This can be rectified by computing a PI that evaluates the effect of the decision. With this in mind, a *PI* model, allowing for measuring the benefit of the control decision and based on passenger delay ($C_{pd}{}^{i'}$), vehicle delay ($C_{oc}{}^{i'}$) and schedule delay($C_{sd}{}^{i'}$) is formulated in this section.

In a multiphase control intersection, the *PI* value should be computed based on the sum of $PI^{i'}$ for each competing phase i', of phase i, in set H.

$$PI = \sum_{i' \in H} PI^{i'} \tag{11}$$

Each $PI^{i'}$ is the sum of the trade-offs due to the signal control decision in $C_{pd}{}^{i'}$, $C_{oc}{}^{i'}$, and $C_{sd}{}^{i'}$.

$$PI^{i'} = C^{i'}_{pd} + C^{i'}_{oc} + C^{i'}_{sd} \quad \forall\, i' \neq i,\ i' \in H \tag{12}$$

In this module the benefit of giving a green is compare with that of terminating it by computing the trade-offs incurred in passenger, vehicle, and schedule delays. The following equations do not reflect the actual passenger, vehicle, and schedule delays.

Computation of Passenger Delay

$$C^{i'}_{pd} = R^{i'}(k) \sum_{\forall l} \left[n_p\, PQ^i_l(k) + \sum_{j=1}^{B^i_l(k)} P^i_{j,l}(k) \right]$$
$$- T \sum_{\forall l} \left[n_p\, PQ^{i'}_l(k) + \sum_{j=1}^{B^{i'}_l(k)} P^{i'}_{j,l}(k) \right] \tag{13}$$

The minimum waiting time for a green for phase i if a switchover occurs is given by

$$R^{i'}(k) = Y^i + AR^i + G^{i'}_{\min} \tag{14}$$

The computation of the total passenger delay in Equation 13 varies with the following scenarios:

- The first term considers the delay of passengers in the green approach resulting from a switchover. If the current green is terminated, then the passengers in the terminated green phase will have to wait for a duration equal to the minimum green time needed for the previous red phase to compete for a switchover.
- If green is extended for phase i by another time step (i.e., for T seconds), then passengers of vehicles in the waiting queue of the competing phase (red phase, i') will suffer an additional delay of T seconds. This is expressed in the second term.

Computation of Vehicle Delay

$$C^{i'}_{oc} = \left[t^p_{sd} \sum_{\forall l} PQ^i_l(k) + t^b_{sd} \sum_{\forall l} B^i_l(k) \right]$$
$$- \left[t^p_{sd} \sum_{\forall l} PQ^{i'}_l(k) + t^b_{sd} \sum_{\forall l} B^{i'}_l(k) \right] \tag{15}$$

The first term expresses the delay of vehicles in queue in the current green phase, i, if their green is terminated. If green is extended

for the current green, then vehicles in the current red phase, $i,'$ will encounter a delay as given in the second term.

Computation of Schedule Delay

$$C_{sd}^{i'} = \sum_{\forall l} \sum_{\forall j} D_{j,l}^{i}(k) - \sum_{\forall l} \sum_{\forall j} D_{j,l}^{i'}(k) \quad (16)$$

The first term denotes the delay of buses in the green approach if their green is terminated, and the second term gives the delay of buses in the red approach if green is extended. If a bus in the green phase is experiencing a delay in schedule, $SD^{i}_{j,l}(k-1)$, when detected, terminating green will result in a delay of $D^{i}_{j,l}(k)$, which is given by

$$D_{j,l}^{i}(k) = R^{i'}(k) + t_{sd}^{b} + (F_{j,l}^{i}(k) - d_{l}^{i}(k) + 1)\frac{3{,}600}{q_s^l} + SD_{j,l}^{i}(k-1) \quad (17)$$

Terminating green at the end of time step k will result in an additional delay caused by

- Minimum waiting time for a green for phase i if a switchover occurs (first term),
- Starting delay, t^{b}_{sd}, for the bus (second term), and
- Time taken to discharge the number of vehicles ahead of the bus, which did not clear the intersection before the end of green.

However, a bus in the red approach will suffer an additional delay due to the extension of green by T seconds. Thus, the total delay of bus j at current red phase i' can be computed with the following equation:

$$D_{j,l}^{i'}(k) = T + t_{sd}^{b} + (F_{j,l}^{i'}(k) - d_{l}^{i'}(k) + 1)\frac{3{,}600}{q_s^l} + SD_{j,l}^{i'}(k-1) \quad (18)$$

Note that the above $PI^{i'}$ should be computed for every competing phase i', of current green phase i, in H. The net PI is the sum of all $PI^{i'}$ If PI is negative, then the optimal decision, with bus-preemption control, is not favorable to the intersection. Hence, it should be changed. If $PI \geq 0$, then the current green should be extended by T seconds.

SYSTEM CONTROL LOGIC

This section deals with the basic control strategy governing the proposed model for adaptive control with bus preemption. Given the aforementioned system and all the functions of its key elements, the operational procedures may be summarized as

Step 1. At time step k and phase i, the system computes the minimum and maximum green times.

Step 2. Checks the minimum and maximum green constraints:

Condition 1: If green time is less than the minimum green time, then the system extends the green ($\xi^{i}(k) = 0$). $U^{i}(k)$ is updated.

Condition 2: If $U^{i}(k)$, the green time used by phase i at time step k, is greater than $G^{i}_{\max}$, then green is terminated immediately. Both parameters $U^{i}(k)$ and $G^{i}_{\min}$ are updated.

Condition 3: If both conditions are satisfied, then the system proceeds to Step 3.

Step 3. Examines bus presence using the bus detectors. If no bus is present, then the number of passengers, $P^{i}_{lj}(k)$, is reduced to zero. Otherwise, it provides all bus presence information.

Step 4. Computes the net benefit of extending green with the proposed PI function.

Step 5. If PI is negative, then the optimal decision is not favorable to the intersection and a switchover decision is taken. Otherwise, it extends the current green by another T seconds.

In the proposed model, the control decision is made every 3 sec depending on a comparison of the benefits of extending green or terminating it. The control logic uses real-time traffic state conditions instead of pre-stipulated strategies. It is assumed in the logic that no bus stop is located between the 36.6 m (120 ft) detector and the stop line. The adopted control strategy is illustrated with a flow chart in Figure 3.

SAMPLE APPLICATION

This section presents a sample application of the proposed system and evaluates its effectiveness under various traffic conditions. All traffic flow-related data for use in the proposed algorithm were generated with TRAF-NETSIM. The key features of all simulated scenarios and evaluation plans are summarized in the next section.

Simulation Experiment

The network considered had a link length of 305 m (100 ft) with 2 lanes in each direction and a bus stop 183 m (600 ft) from the stop line. There was no bus bay. To facilitate the functioning of the proposed system, the surveillance environment included a stop line detector and detectors at 36.6 m (120 ft) and 289.75 m (950 ft) per lane for each direction. Signal control operations were designed with a two-phase actuated control, permitted left turns, minimum green of duration 15 sec, maximum green of 60 sec, and a yellow of 3 sec.

Two bus route arrivals were simulated for northbound and southbound approaches and one each for east- and westbound approaches. The experimental data were collected for 10 min after the initialization period. The proposed model was tested for 90 time intervals, each of duration 3 sec. The traffic volume varied as 300 vphpl, 500 vphpl, and 1000 vphpl. The mean discharge headways of buses were taken as 180 sec (20 buses/hr) and 120 sec (30 buses/hr).

The layout of the experimental intersection is given in Figure 4. The traffic variables were collected only to provide a meaningful data set for evaluating the performance of the control logic. Because the purpose of the experiment was to test the model, the entering traffic volume was taken as a constant. The algorithm used the following traffic measurements from NETSIM's output:

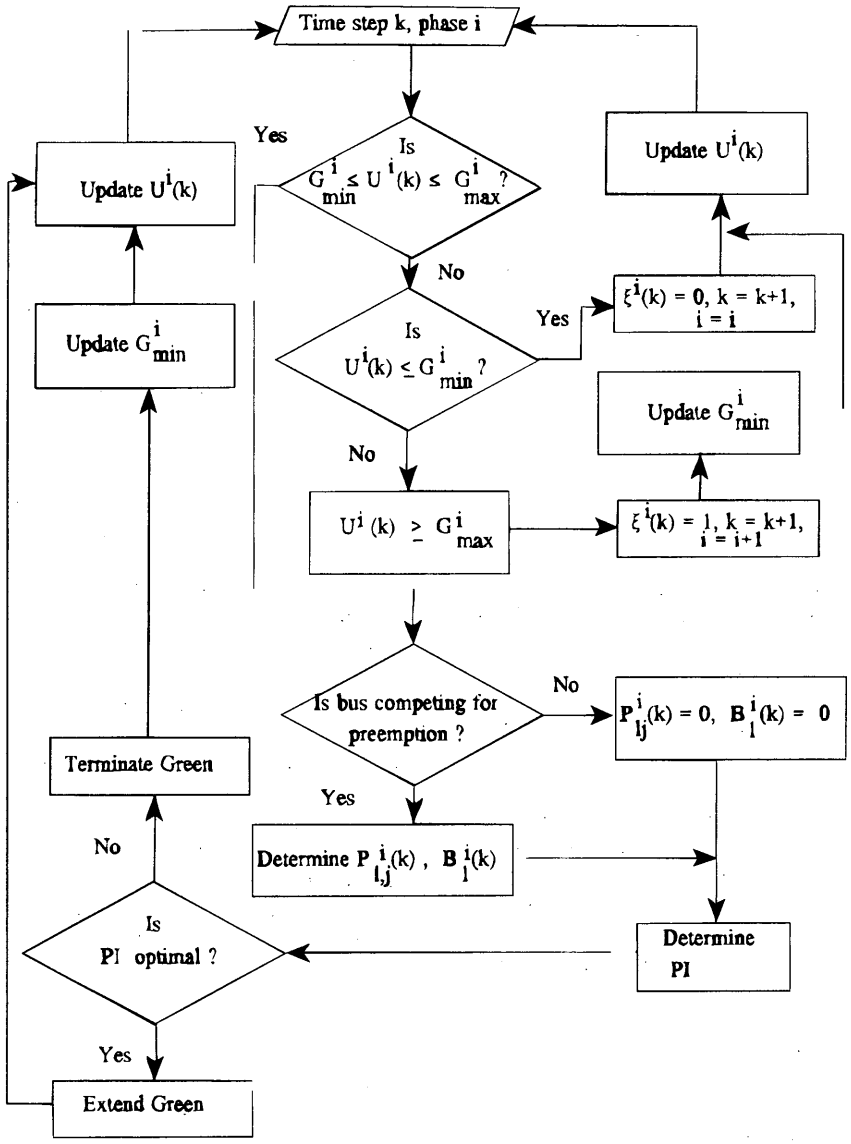

FIGURE 3 The control logic for bus preemption.

- Queue length at the beginning of the first time step in the experiment;
- Number of passenger car arrivals from the information supplied by the 36.6-m (120-ft) and 289.75-m (950-ft) detectors to estimate queue length; and
- Number of bus arrivals from the bus detector at 36.6 m (120 ft) to include in the preemption function and to estimate bus queue length.

To conform with the proposed control logic that a bus shall compete for preemption only when detected by the 36.6 m (120 ft) detector, the number of passengers in a detected bus were assigned according to a normal distribution with mean 15 and standard deviation 2.5. A schedule delay was designated, assumed to be uniformly distributed between 0 and 10 min. If a bus was not detected, the number of passengers and the schedule delay were recorded as zeros in the *PI* function.

Model Performance Evaluation

Based on the simulation output, the following computation procedure was used for testing the algorithm.

Criterion for Testing Performance of Adaptive Control over Actuated Control

The performance was tested based on the total queue length recorded at the end of every 3 sec for the entire intersection. Since

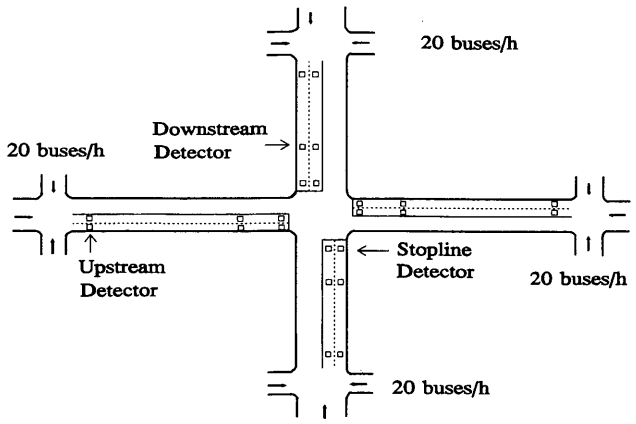

FIGURE 4 Layout of the experimental intersection.

NETSIM does not include a bus-preemption function, the model was first compared, without considering preemption, with the actuated control model of NETSIM for passenger car volumes of 500 vphpl and 1000 vphpl, and mean bus headway of 180 sec.

Criterion for Testing Performance of Adaptive Control With Preemption and Without Preemption

Having analyzed the effectiveness of adaptive control without preemption, the performance of the proposed model was studied. Hence, the total passenger delay at the intersection as a result of the signal control decision, with and without giving bus preemption, was investigated for passenger car volumes of 300 vphpl, 500 vphpl, and 1000 vphpl, and mean bus headways of 120 and 180 sec.

Discussion of Experimental Results

Following the first criterion for evaluating the performance of the proposed model without a preemption function, graphs (Figures 5 and 6) were drawn (*a*) for the total queue length at the intersection, (*b*) for each control time step for 90 time intervals (each of duration 3 sec) for the different listed cases, and (*c*) for both adaptive and actuated control logics.

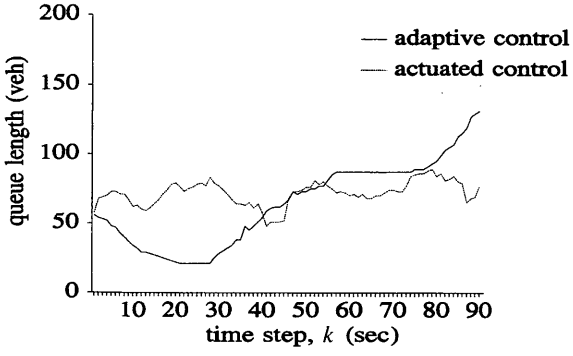

FIGURE 5 Total queue length for the demand level of 500-vphpl and 180-sec bus discharge headway.

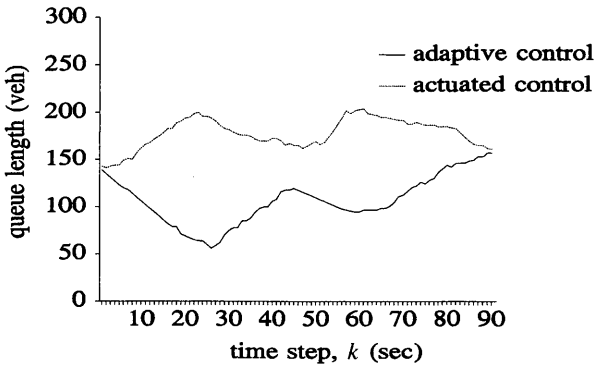

FIGURE 6 Total queue length for the demand level of 1,000-vphpl and 180-sec bus discharge headway.

Figures 5 and 6 show that the adaptive control logic yielded results superior to those of the actuated control simulated by NETSIM. For demand levels of 500 vphpl (Figure 5), and 1000 vphpl (Figure 6), the overall queue length for the actuated control model was more than the adaptive algorithm by 10 to 15 percent and 40 to 45 percent, respectively. For highly congested flow (1,000 vphpl), the adaptive control queue length was found to be less than the actuated control queue length for the entire test period. Thus, it may be concluded that adaptive control even without bus-preemption operation is superior to the actuated control under all traffic conditions.

To investigate the performance of the algorithm with preemption, graphs were drawn for (*a*) the total delay at the intersection for the different traffic scenarios under the second criterion and (*b*) the model with and without preemption. The total delay for the adaptive control logic with and without preemption is listed in Table 2 for all indicated scenarios. As observed in Table 2, the proposed adaptive control model with bus-preemption function was superior to the logic without preemption for all traffic volume conditions.

For Scenarios 1 (300 vphpl and 180 sec) and 2 (300 vphpl and 120 sec) in Figure 7, the algorithm without preemption produced 80 to 90 percent more delay than the one with preemption. For very heavy traffic conditions (1,000 vphpl), with mean bus discharge headways of 180 sec and 120 sec (Figure 8), the control logic with preemption produced adequately better results than the strategy without preemption. There also was an increase in the total delay for the control logic without preemption by 1 to 10 percent for the two discharge headways.

These results show that the proposed model performs well under light-to-moderate traffic volume situations, but exhibits a slight decrease in the benefit as the traffic state becomes highly congested. The reason is that under heavy congestion the total number of bus passengers in the queue have to compete with the long passenger car queue length for priority. Hence, a fair competition for very low bus volume does not exist. Despite the large difference in the two volumes, the proposed system exhibited a better performance than the logic without a preemption function. In the experiment, the random number of passengers assigned to a bus was assumed to follow a normal distribution with mean 15 and standard deviation 2.5. Varying the mean of the distribution from 5 to 30 and the standard deviation from 0.5 to 2.5 did not affect the superior performance of the proposed logic. Thus, the experimental results indicate the superiority of the devised model under all traffic conditions.

TABLE 2 Total Delay for the Adaptive Control Logic With and Without Preemption

Traffic Volume Delay (vphpl)	Mean Bus Discharge Headway (seconds)	Total Delay (seconds)		% Increase in for Model Without Preemption
		Without Preemption	With Preemption	
300	180	24,342	3483	85
300	120	25,470	4833	81.1
500	180	34,044	18,609	45.34
500	120	33,303	22,020	33.88
1000	180	57,990	57,195	1.37
1000	120	60,372	55,869	7.46

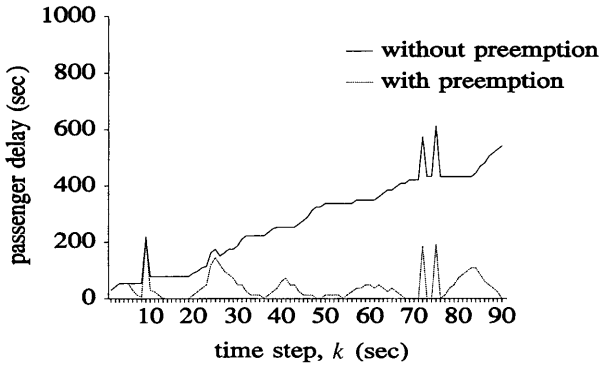

FIGURE 7 Total delay at the intersection for the demand level of 300-vphpl and 180-sec bus discharge headway.

CONCLUSIONS AND FURTHER RESEARCH

A model was formulated for an integrated adaptive control system with bus preemption and signal control functions. In the proposed model, absolute priority was not given to a bus. The model applied real-time algorithms instead of prespecified strategies used by more conventional bus-preemption logic. Driver safety and overall minimization of queue length were the two deciding factors when imposing the minimum green requirement. The control decision for signal setting was based on a performance index, which incorporated bus schedule delay, passenger delay, and vehicle delay.

Real-time traffic variables from the output of TRAF-NETSIM were used to test the performance of the algorithm. The experimental results proved the superiority of the proposed model over the actuated control logic simulated by NETSIM, under all traffic conditions. Hence, it may be concluded that the model performed favorably under all traffic volume states.

It should be noted that the primary focus of this article was to investigate the process of integrating bus-preemption and adaptive signal control. Hence, only a simple myopic adaptive logic was employed in the proposed system. An enhanced version of the proposed system, which uses information from both neural network prediction models and AVL systems for optimizing signal control over a projected time horizon, has also been developed and is available elsewhere (Chang et al., unpublished data).

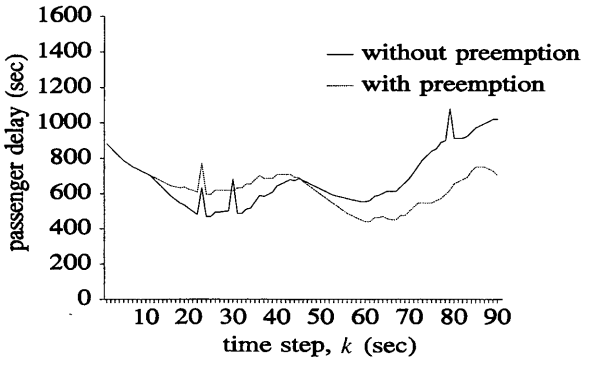

FIGURE 8 Total delay at the intersection for the demand level of 1000-vphpl and 120-sec bus discharge headway.

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