Effective Coordinated Optimization Model for Transit Priority Control Under Arterial Progression

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With the goal of providing effective priority control for transit while minimizing adverse impacts on general traffic movements along the arterial, this paper presents a coordinated transit priority control optimization model with the following features: (*a*) the control unit is defined as the coordinated intersection group between two successive bus stops; (*b*) buses are detected after leaving the upstream stop before their arrival at the first intersection of a control unit; (*c*) the dynamic interactions of priority strategies between adjacent intersections within a control unit are modeled by using a bus delay model and an ineffective priority time model; and (*d*) a linear program model is developed to generate the optimal priority strategies to reduce bus travel time when priority is necessary and to ensure that every priority treatment implemented at each intersection is effective. Extensive experimental analyses, including time–space diagram-based deterministic analysis and simulation-based analysis, were performed, and results were compared with conventional transit signal priority strategy and no-priority scenarios. The proposed model presents promising outcomes in the design of transit priority signal control in terms of decreasing bus delay, improving bus schedule adherence, and minimizing the negative impacts on general traffic under different traffic demand patterns.

Traffic congestion has been one of the most depressing and challenging problems of the urbanization process in China. An increasing number of researchers have recognized that providing reliable public transportation service is one of the most effective strategies to relieve traffic congestion. Compared with the large amount of resources invested in transit infrastructures, transit signal priority (TSP) is a promising and low-cost solution. With TSP, buses can request the green phase of traffic signals and progress unimpeded through an arterial without stopping. Properly designed TSP strategies will significantly reduce the travel time and improve the reliability of the transit system. Therefore, TSP has become a key component in the urban traffic control system.

Wilbur Smith and Associates et al. conducted the earliest bus preemption experiment, which gained significant reduction in bus travel times (*1*). Since then, many studies have proposed TSP strategies and reported benefits of various practices. Most of the literature has focused on designing transit signal control logic or algorithms for isolated signalized intersections (*2–7*) and evaluation and comparison of TSP strategies using simulation data or field data (*8–14*).

Conditional priority strategies provide priority only to those buses that are behind schedule and whose reliability can be improved (*15–17*). Signal priority strategies have also been used for bus headway control (*18*). Traffic signal control systems such as SCOOT, SCATS, and RHODES have embedded bus priority logic in the software that provides transit signal priorities at the local or system level (*19–21*). The impacts of transit facilities (e.g., exclusive bus lanes and bus stops) on TSP have also been investigated (*22, 23*).

Despite the promising progress in these studies, there is insufficient research on designing effective optimal transit priority signals in response to bus requests at coordinated intersections along an arterial. The consideration of coordination in TSP control was proposed in the 1990s (*24*). The evaluation of the effects of TSP on general traffic further demonstrated the importance of incorporating signal coordination into TSP control systems (*16, 25*). A new method of doing this was developed by minimizing a performance index function of bus schedule delay, automobile delay, and bus passenger delay subject to bandwidth and minimum green constraints (*26*). Minimizing bus travel time was also used as an objective function to optimize coordinated signal plans for buses (*27*).

One problem with existing bus priority algorithms is that the bus arrival times at downstream intersections are not considered in the decision to provide priority at upstream intersections. The coordination of priority strategies between sequential intersections is essential to ensure each priority treatment implemented at each intersection is effective. For example, advancing the green time at the upstream intersection may result in additional bus delay at the downstream intersections and lead to no overall delay savings. Moreover, in many systems, detection occurs no farther than the stop line of the closest upstream intersection. This practice limits the degree to which the traffic signal can be adjusted to serve approaching buses, especially in cases of long clearance times for pedestrian crossings, which is an important concern on transit arterials. With such short notice, aggressive priority strategies can seriously disrupt the general traffic (*28*).

The research in this paper develops a new coordinated TSP model that includes the following features:

1. The basic control unit, defined as a group of coordinated signalized intersections between two bus stops (buses are detected after leaving the upstream stop before arriving at the first intersection of the control group);

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2. A new TSP control framework that can provide coordinated bus priority control for bus priority requests at each intersection of the coordinated control group;
3. A simple linear program model to produce the optimal signal timings for bus priority requests at every intersection of the coordinated control group; and
4. A demonstration of the effectiveness of the proposed model with an illustrative case study and sensitivity analyses of critical factors affecting the model performance.

The paper is organized as follows. In the next section, the design of the coordinated control framework and the assumptions and notation adopted in this paper are described. The formulation of bus delay and ineffective priority times are proposed in the third section. The coordinated optimization model is presented in the fourth section, and the fifth section evaluates the proposed model on the basis of numerical analysis and simulation results. Conclusions are given at the end of the paper.

CONTROL FRAMEWORK

Basic Control Concept

Coordinated Control Group: From Bus Stop to Bus Stop

A major issue with TSP implementation is the location of bus stops and, more specifically, the uncertainty that exists about the time a bus will remain immobilized at a stop to board and discharge passengers. The decision whether a bus should be given priority depends on bus arrival time and schedule at every bus stop. For this study, the coordinated controlled arterial was divided into several coordinated groups that were based on the location of bus stops (Figure 1*a*). Each coordinated group spanned from one bus stop to the next bus stop. Bus detectors were located downstream of the first bus stop and provided bus arrival time information for the coordinated control algorithm.

Conditional Priority Strategy: Systematic Optimization

In order to generate effective priority strategies for buses, as well as to minimize adverse impacts on general traffic, priority treatments were only provided to the buses that were truly in need of priority as measured by defined bus operation criteria, primarily schedule deviation caused by lateness. If the estimated schedule deviation exceeded the permitted deviation by a user-defined amount, the bus was considered to be priority eligible and was granted priority treatment at the group of intersections; otherwise, the bus was not granted priority. To avoid significantly affecting progression on the arterial, the cycle length, phase sequence, and offsets were maintained, and a set of predefined limitations was used to limit the use of aggressive priority strategies and ensure a high level of service for regular traffic.

Priority Control Objective: Minimize Travel Time and Ineffective Priority Time

The contribution of a priority treatment implemented at one intersection to the objective (minimizing schedule deviation or travel time) is relevant to the priority strategies at downstream intersections (*27*). In Figure 1*b,* after a bus receives priority (green extension) at intersection *i,* it can pass intersection $i + 1$ without delay (trajectory shown by the dotted line), and the total travel time is reduced dramatically compared with the no-priority situation (trajectory shown by the solid line). Therefore, the priority strategy implemented at intersection *i* is effective. However, in Fig-

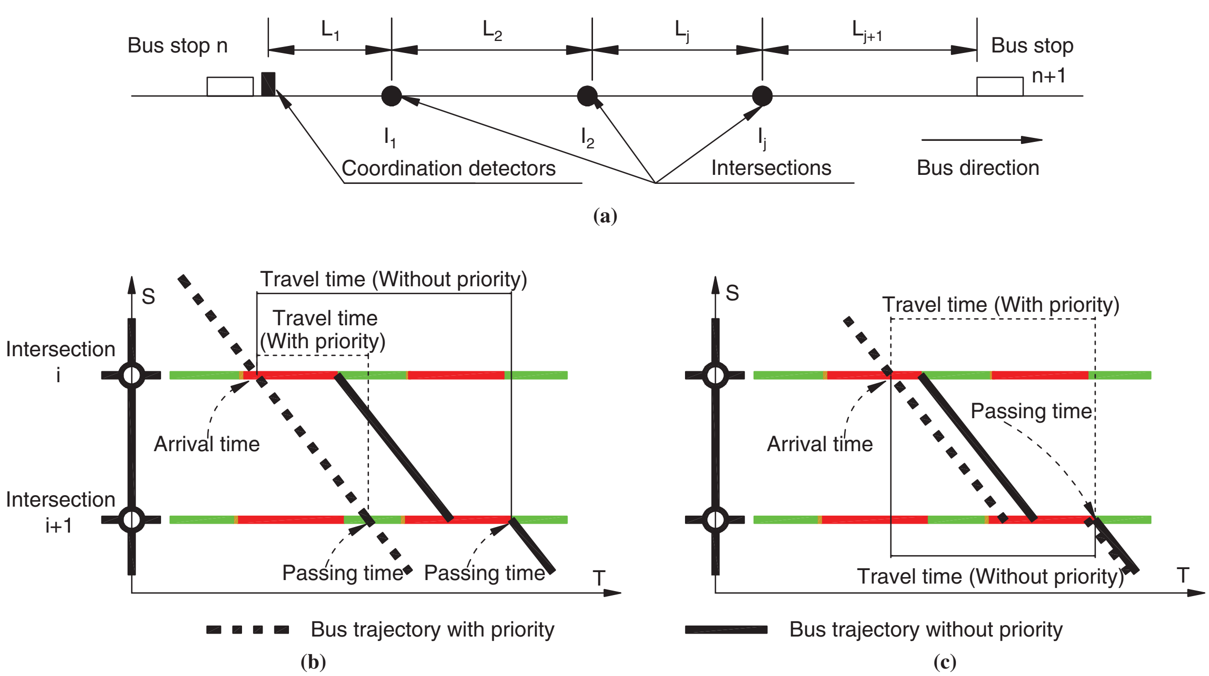


FIGURE 1 Basic control concept: (*a*) coordinated control group, (*b*) effective priority, and (*c*) ineffective priority.

ure 1*c,* the bus receives a priority treatment (red truncation) at intersection *i* and has to wait for the green time at intersection *i* + 1 (it is assumed that no effective priority can be provided at intersection *i* + 1 at that time), and the total delay is unchanged compared with the no-priority situation. Hence, the priority strategy implemented at intersection *i* is ineffective in term of decreasing bus travel time. To ensure that all priority treatments used in every intersection were effective, both travel time and ineffective time were taken into account in the objective function proposed in this paper.

Model Assumptions

To yield a tractable solution for the proposed formulations with realistic constraints, this study employed the following assumptions:

1. There is a background coordinated signal plan for the route, and the intersections in the coordinated group are a subset of the coordinated intersections in the background signal plan;
2. Bus speed at the *i*th link (v_i) is a constant;
3. There is an exclusive bus lane, no queue exists at the bus approaches, and the acceleration and deceleration delay are neglected;
4. Only one transit priority request can be served in one cycle. The first-come, first-served rule is applied for multiple priority request situations; and
5. For simplicity, the start of the green phase for the bus is set to zero.

These assumptions are suitable for exclusive bus lane operation or a bus rapid transit system. In a mixed-traffic situation, the model framework is still suitable, but a bus delay model should be extended to address the variation of bus speed and impacts of other vehicles.

Notation

All definitions and notations used in the model formulation are summarized in Table 1.

TABLE 1 Notation and Parameters

L_i	Length of link *i* (m)
v_i	Bus speed at link *i* (m/s)
k_i	Signal time of bus arrival at intersection *i* (s)
k_0	Signal time of bus arrival at upstream coordination detector
t_i^a	Arrival time of bus at intersection *i* (s)
t_i^d	Delay of bus at intersection *i* (s)
t_i^l	Time needed for bus to travel through link *i* (s)
t^E	Arrival time of bus at ending bus stop of control group (s)
t_E^P	Scheduled bus arrival time at ending bus stop of control group (s)
δ_i	Type of priority strategy used at intersection (green extension and red trunction)
g_i^e	Green extension time (s)
g_i^t	Red truncation time (s)
$g_{\max}^e$	Maximum green extension time (s)
$g_{\max}^t$	Maximum red truncation time (s)
C	Common cycle length (s)
t_i^n	Arrival time of bus without priority control at intersection *i*
t_i^e	Expected passing time of bus that has received effective priority treatments at intersection *i*
t_i^w	Ineffective priority time of priority treatment at intersection *i* (s)
O_i	Offset between (*i*–1)th intersection and *i*th intersection
I_i	Intergreen (amber and all red time) time between *j*th phase and next phase (s)
g_{ij}	The *j*th phase length of *i*th intersection in background signal plan (s)
$g_{i,j}^c$	Length of *j*th phase of *i*th intersection in priority control plan (s)
P_i	Number of phases of intersection *i* (s)
g_i^p	Length of priority time in phase *p* (s)

FORMULATIONS OF BUS DELAY AND INEFFECTIVE PRIORITY TIME

Bus Arrival Time

The arrival time of a bus that had passed the starting bus stop and coordination detector at every intersection of the control group was decided by three factors: arrival time at the upstream intersection, delay at the upstream intersection, and travel time from the upstream intersection to the downstream intersection.

Travel time t_i^l at every link *i* can be calculated by Equation 1:

$$t_i^l = \frac{L_i}{v_i} \qquad i = 2, 3, \ldots, N \tag{1}$$

The arrival time of the bus at the first intersection can be computed with Equation 2:

$$t_1^a = t_1^l \tag{2}$$

In Equation 2, t_1^l is the bus travel time on Link 1 (L_1 as shown in Figure 1*a*). The arrival time of a bus at every downstream intersection can be computed with Equation 3:

$$t_i^a = t_{i-1}^a + t_i^d + t_i^l \qquad i = 2, 3, \ldots, N \tag{3}$$

Thus, the arrival time of the bus at the ending bus stop can be computed with Equation 4:

$$t_E = t_N^a + t_N^d + t_{N+1}^l \tag{4}$$

In Equation 4, t_{N+1}^l is the time needed for the bus to travel from the last intersection of the control group to the ending stop.

Priority Request Generation

A priority algorithm must be able to assess approaching buses and grant priority only to those buses that will truly benefit from priority. Predicted bus schedule adherence is defined as a state in which the predicted bus arrival time at the ending bus stop is within a specified variance from its scheduled arrival time according to a predefined bus schedule. The predicted bus arrival time at the ending bus stop is compared with the scheduled bus arrival time to determine whether the scheduled bus is delayed and by how long. If the predicted bus arrival time exceeds the scheduled bus arrival time by a user-defined amount, the bus is considered to be late and is granted a priority strategy in the intersection control group. If, however, the predicted bus arrival time does not exceed the scheduled arrival time by a user-defined amount, then the bus is not granted priority. Gamma (γ) is defined as a binary variable with a value of 1 (provide priority to the bus) or 0 (do not provide priority to the bus); γ can be calculated by Equation 5:

$$\gamma = \begin{cases} 1 & t_E - t_E^P > \theta \\ 0 & t_E - t_E^P \le \theta \end{cases} \tag{5}$$

Available Priority Strategies

The two types of TSP strategies (green extension and red truncation) that were used are based on background signal timings (Figure 2). Phase insertion strategy was not used in order to avoid a deleterious effect on the background signal coordination. A variable (δ_i) was defined to represent the type of priority strategy used at intersection *i,* as shown in Equation 6:

$$\delta_i = \begin{cases} 1 & \text{green extension} \\ 0 & \text{no priority} \\ -1 & \text{red truncation} \end{cases} \tag{6}$$

where $\delta_i = 1$ and $\delta_i = -1$ indicate that the green extension or red truncation treatment, respectively, was selected at intersection *i;* and $\delta_i = 0$ means no priority treatment was used at intersection *i.*

Bus Delay Model

According to the first assumption, bus delay at an intersection is equal to the rest time of the red signal when the bus arrives at the stop line. Therefore, bus delay at the intersection is decided by two factors: signal status when the bus arrives at the intersection, and the priority strategy used at the intersection.

The signal status when the bus arrives at the stop line of the first intersection (k_1) is the arithmetical complement of $k_0 + t_i^l$ divided by cycle length *C.* It can be calculated by Equation 7:

$$k_1 = \left(k_0 + t_i^l\right) \text{mod}(C) \tag{7}$$

The signal status when the bus arrives at the stop line of the *i*th intersection (k_i) can be calculated by Equation 8:

$$k_i = \left(k_{i-1} + t_i^l - O_i + t_i^d\right) \text{mod}(C) \qquad i = 2, 3, \dots, n \tag{8}$$

According to the definition of k_i, if k_i is less than g_i, then bus delay is zero; otherwise, bus delay is equal to the rest of the red time. Therefore, if no priority is provided at intersection *i,* the delay of the bus at intersection *i* can be calculated by Equation 9:

$$t_i^d = \begin{cases} 0 & 0 < k_i \le g_{i,1} \\ C - k_i & g_{i,1} < k_i \le C \text{ and } \delta_i = 0 \end{cases} \tag{9}$$

As shown in Figure 2, if $g_{i,1} < k_i \le g_{i,1} + g_{\max}^e$, then the green extension strategy can be used to provide priority. Otherwise, if $g_{i,1} < k_i \le C,$ then the red truncation strategy can be used to provide priority.

The green extension strategy will be useless if the extended ending time of the green signal is still less than bus arrival time. The green extension time can be calculated by Equation 10:

$$g_i^e = \begin{cases} 0 & \delta_i \ne 1 \\ k_i - g_{i,1} & \delta_i = 1 \end{cases} \tag{10}$$

Therefore, if $g_{i,1} < k_i \le g_{i,1} + g_{\max}^e$ and green extension is used, the bus delay at intersection *i* can be calculated by Equation 11:

$$t_i^d = 0 \qquad g_{i,1} < k_i \le g_{i,1} + g_{\max}^e \text{ and } \delta_i = 1 \tag{11}$$

If $g_{i,1} < k_i \le C$ and the red truncation strategy is used, then bus delay at intersection *i* can be calculated by Equation 12:

$$t_i^d = C - g_i^t - k_i \qquad g_{i,1} < k_i \le C \text{ and } \delta_i = -1 \tag{12}$$

In summary, bus delay at intersection *i* can be calculated by Equation 13:

$$t_i^d = \begin{cases} 0 & 0 < k_i \le g_{i,1} \\ C - k_i & g_{i,1} < k_i \le C \text{ and } \delta_i = 0 \\ 0 & g_{i,1} < k_i \le g_{i,1} + g_{\max}^e \text{ and } \delta_i = 1 \\ C - g_i^t - k_i & g_{i,1} < k_i \le C \text{ and } \delta_i = -1 \end{cases} \tag{13}$$

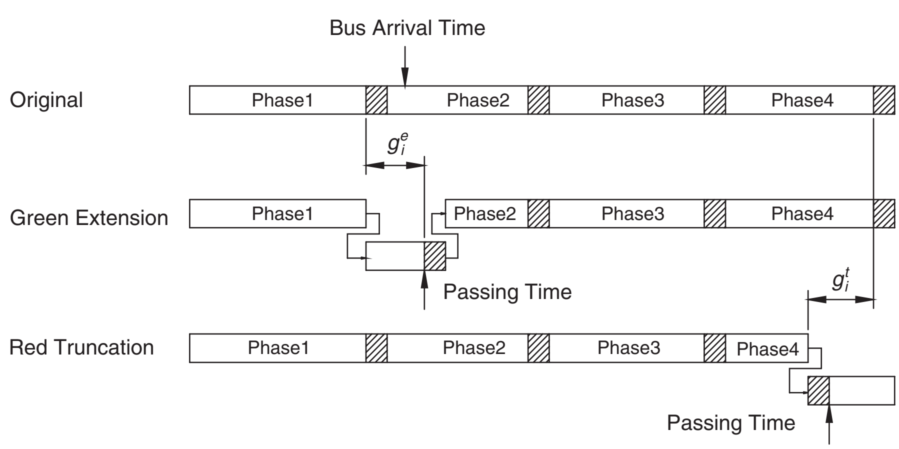


FIGURE 2 Bus signal priority strategies.

Ineffective Priority Time Model

Figure 3 shows the different combinations of effective priority and wasted priority strategies among three intersections. The solid lines represent the trajectories of buses receiving no priority treatments, the bold dotted lines represent the trajectories of buses receiving priority treatments, and the thin dotted lines represent the trajectories of buses receiving only effective priority treatments. As the figure shows, the effectiveness of a priority strategy adopted at one intersection is determined by whether the priority strategy can decrease the total travel time of buses traveling to all the downstream intersections compared with the no-priority scenario. Moreover, the effectiveness of a priority treatment at a downstream intersection affects the effectiveness of priority treatments implemented at all upstream intersections. Note that although one priority treatment may be effective, part of a priority time might be wasted time, as shown in Figure 3 (Case 1, red truncation).

The total bus travel time from bus detectors to intersection *i* can be calculated from bus arrival time and bus passing time at intersection *i*. Variable t^n_{i+1}, which is used to represent the arrival time

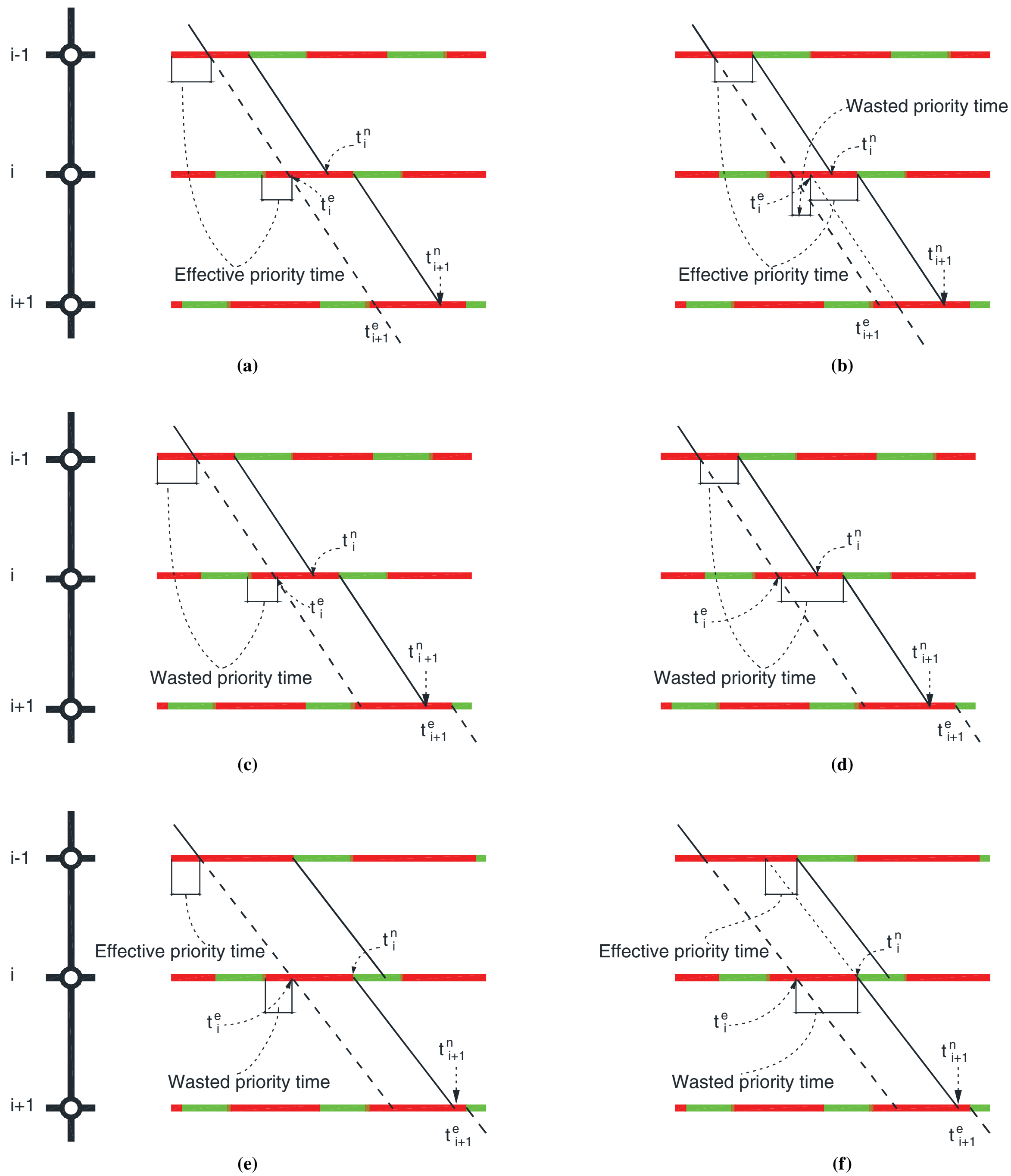


FIGURE 3 Effectiveness analysis of priority treatments: (*a*) green extension and (*b*) red truncation, Case 1 (effective + effective); (*c*) green extension and (*d*) red truncation, Case 2 (ineffective + ineffective); and (*e*) green extension and (*f*) red truncation, Case 3 (effective + ineffective).

at intersection i + 1 of the bus without priority control, can be calculated by Equation 14:

$$t_{i+1}^{n} = t_i^a + t_i^d + t_{i+1}^{l} \tag{14}$$

Variable ε_i is defined to represent whether the priority strategy used in one intersection can decrease the total travel time, as shown by Equation 15:

$$\varepsilon_i = \begin{cases} t_{i+1}^{n} - t_{i+1}^{e} & \delta_i \neq 0 \\ 0 & \delta_i \neq 0 \end{cases} \qquad i = 1, 2, \ldots, N-1 \tag{15}$$

In Equation 15, t_{i+1}^{n} is the arrival time at intersection i + 1 of the bus that has received no priority at intersection i, and t_{i+1}^{e} is the expected passing time of the bus that has received effective priority treatments at intersection i + 1. As shown in Figure 3, $\delta_i = 0$ means that there is no priority strategy implemented at intersection i and no ineffective priority time at intersection i. If $\delta_i \neq 0$ and $\varepsilon_i > 0$, then the priority strategy implemented at intersection i is useful in decreasing the total travel time. If $\delta_i \neq 0$ and $\varepsilon_i \leq 0$, then the priority strategy implemented at intersection i is no use in decreasing the total travel time (i.e., it is an ineffective priority treatment).

For the final intersection N, all priority strategies are effective because there are no downstream intersections, and the expected passing time at N can be calculated by Equation 16:

$$t_N^e = t_N^a + t_N^d \tag{16}$$

For the rest of the intersections in the control unit, the expected passing time is determined by priority treatment type (green extension or red truncation) and the effectiveness of the priority treatment, which can be calculated by Equation 17:

$$t_i^e = \begin{cases} t_i^a + t_i^d & t_i^w = 0 \\ t_i^a + C - k_i & t_i^w > 0, \delta_i = 1 \\ t_i^a + C - k_i - \left(t_{i+1}^{n} - t_{i+1}^{e}\right) & t_i^w > 0, \delta_i = -1 \end{cases} \tag{17}$$

In Equation 17, $t_i^e = t_i^a + t_i^d$ means that the expected passing time is equal to the actual passing time if the priority strategy used at intersection i is effective; $t_i^e = C$ means the expected passing time is equal to cycle length if a green extension is used and the strategy is ineffective; and $t_i^e = C - [t_{i+1}^{n} - t_{i+1}^{e}]$ means the expected passing time is equal to the difference between the cycle length and the effective part of the priority time.

For intersection i, the ineffective priority time can be calculated by Equation 18 on the basis of ε_i:

$$t_i^w = \begin{cases} t_i^{w^*} & \varepsilon_i > 0, \delta_i \neq 0 \\ g_i^e + g_i^t & \varepsilon_i \leq 0, \delta_i \neq 0 \\ 0 & \delta_i = 0 \end{cases} \qquad i = 1, 2, \ldots, N-1 \tag{18}$$

In Equation 18, $t_i^w = 0$ means that no priority time is wasted at intersection i; $t_i^w = g_i^e + g_i^t$ means that the priority strategy (either green extension or red truncation) implemented at intersection i is useless in terms of decreasing travel time; and $\varepsilon_i > 0$ means that at least part of the green time provided at intersection i is useful, and only $t_i^{w^*}$ priority time is ineffective time. According to Figure 1b, $t_i^{w^*}$ is related to the strategies implemented at intersection i and can be calculated by Equation 19:

$$t_i^{w^*} = \begin{cases} 0 & \delta_i = 1 \\ g_i^t - \left[t_{i+1}^{n} - t_{i+1}^{e}\right] & \delta_i = -1 \end{cases} \tag{19}$$

In Equation 19, $t_i^{w^*} = 0$ means that if $\varepsilon_i > 0$ and a green extension strategy is used to provide priority at intersection i, then no priority time is wasted (this situation occurs because the extension time must be the bus arrival time, at least at intersection i, if green extension is selected); $t_i^{w^*} = g_i^t - [t_{i+1}^{n} - t_{i+1}^{e}]$ means that if $\varepsilon_i > 0$ and red truncation strategy is used to provide priority, the ineffective time is equal to the time difference between total red truncation time and effective red truncation time ($t_{i+1}^{n} - t_{i+1}^{e}$).

EFFECTIVE COORDINATED OPTIMIZATION MODEL

With the above bus delay and ineffective priority time formulations, the following model was constructed to optimize transit priority signal timings for the control unit, including the priority strategy type and priority time.

Objective Function

Given a bus priority request, Equation 20 represents the objective of the control model for minimizing the total travel time spent by the bus in the control unit and for minimizing the ineffective time of priority strategies implemented at each intersection in the control unit.

$$\text{minimize } t_E + \varnothing \sum_{i=1}^{N} t_i^w \tag{20}$$

where t_E represents the travel time of the bus within the control unit, which is the primary objective of this model, and $\sum_{i=1}^{N} t_i^w$ is the sum of ineffective priority time, which is the supplement of the primary objective. A small positive integer parameter ($\varnothing$) is used to ensure that the effects of the second term will not negate that of the first term.

Control Variables

Control variables are as follows: δ_i is the priority strategies type and g_i^p is the priority time at each intersection.

Constraints

Equations 1 to 3 and 5 to 17, representing the dynamic traffic state evolution along the arterial, are the principal constraints for the control model. The following constraints for the signal control parameters should also be included.

Allocation of Priority Time Constraints

Priority time g_i^p can be directly calculated by Equation 21:

$$g_i^p = \begin{cases} g_i^e & \delta_i = 1 \\ 0 & \delta_i = 0 \\ g_i^t & \delta_i = -1 \end{cases} \tag{21}$$

To keep cycle length unchanged, it is obvious that other phases should be compressed to provide g_i^p. The compressed time of each phase is weighted by saturation and can be calculated by Equation 22:

$$g_{i,j}^c = g_{i,j} + \frac{x_{ij}}{\sum_{j=1}^{P_i} x_{ij}} g_i^p \qquad \forall i, j = 2, 3, \ldots, P_i \tag{22}$$

Cycle Length Constraints

The cycle length constraint is used to keep the signal progression of the intersection group. It is a simple equation constraint, and for a given intersection *i,* it can be calculated by Equation 23:

$$\sum_{j=1}^{P_i} \left(g_{i,j}^c + I_i\right) + g_i^p = C \tag{23}$$

Priority Time Constraints

To avoid deleterious effects on the background coordinated signal plan, the available priority time for both green extension and red truncation should be limited. The permitted value of priority time is an input of the model; it can be a constant or a time-dependent value. The constraints on priority time can be represented by Equations 24 and 25:

$$g_i^e \le g_{\max}^e \tag{24}$$

$$g_i^t \le g_{\max}^t \tag{25}$$

EVALUATION

Experiment Design

To illustrate the efficiency and applicability of the proposed model, a sample arterial consisting of four intersections and four bus stops was examined in a case study. The basic layouts of the arterial and phase configurations are given in Figure 4.

The turning fractions for all intersection approaches were set to be 30% left turn, 60% through, and 10% right turn. This numerical test included 10 demand entries (A to J in Figure 4) and three volume levels (low, medium, and high) designed to test the performance of the proposed control model. The maximum and minimum green extension and red truncation time was 10 s. Table 2 summarizes all experimental scenarios.

To test the capability of the proposed model of generating optimal TSP timings and avoiding ineffective priority time, the three scenarios listed below were compared:

1. Effective coordinated TSP (ETSP) control. The priority treatments of each intersection were optimized by the proposed model on the basis of background signal plans obtained from Synchro 7;
2. Coordinated control without priority (NTSP). The coordinated signal plans generated by Synchro 7 were directly used, and no priority treatments were given for any buses; and
3. Conventional TSP (CTSP) control. Conventional priority treatments (e.g., green extension and red truncation) were given to each bus according to the background signal timings generated by

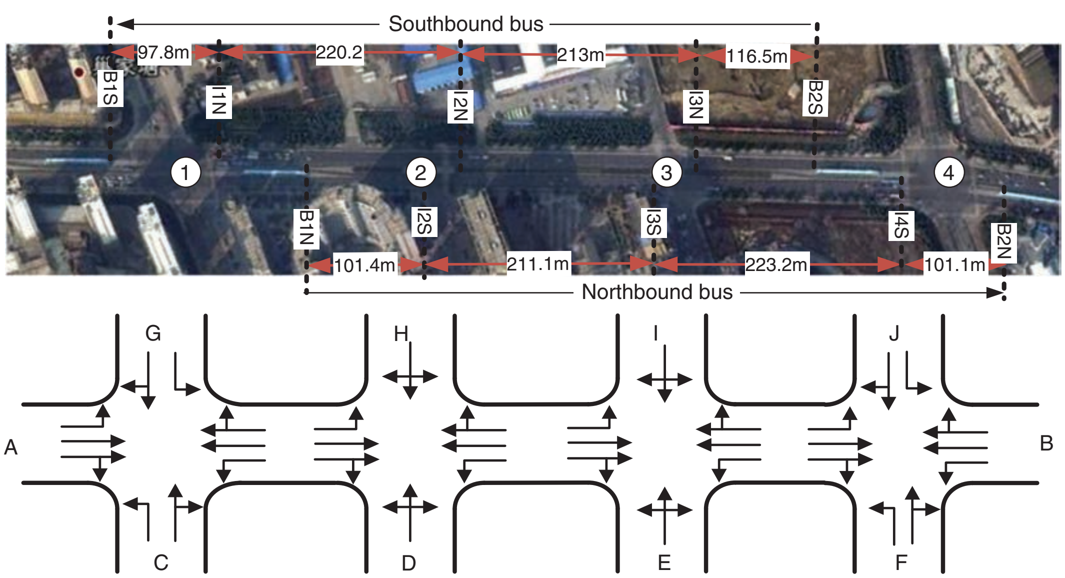


FIGURE 4 Experimental arterial layout and phase settings.

TABLE 2 Experimental Scenarios for Model Evaluation

Traffic Mode	Demand Scenario	Degree of Saturation	Demand Entries (vph) A	B	C	D	E	F	G	H	I	J
General traffic (GT)	Low	0.6	600	600	400	100	100	400	400	100	100	400
	Medium	0.8	900	900	600	150	150	600	600	150	150	600
	High	1	1,200	1,200	800	200	200	800	800	200	200	800
Transit	Low	na	40	40	na	na	na	na	na	na	na	na
	High	na	120	120	na	na	na	na	na	na	na	na

NOTE: vph = vehicles per hour; na = not applicable.

Synchro 7. Table 3 shows the background signal timings optimized by Synchro under the different demand levels defined in Table 2.

Time–Space Diagram-Based Deterministic Analysis

In this analysis, buses were assumed to be traveling with deterministic speed. The time–space diagram method was used to analyze the performance of the proposed method, as shown in Figure 5 and Table 4. Twenty priority requests (10 for each direction) were selected randomly and provided priority in 20 cycles (per request per cycle). The trajectories of each bus were projected in two cycles as shown in Figure 5. The solid lines represent the trajectories of each bus under CTSP control, and the dotted lines represent the trajectories of each bus under ETSP control. The trajectories of Requests 1, 2, 7, 8, 9, and 10 of the northbound direction under the control of CTSP and ETSP are coincident (solid lines), but the trajectories between I2S and B2N of Requests 3, 4, 5, and 6 are the same dotted line under ETSP control, which differ from the trajectories under CTSP control. The trajectories of Requests 13, 14, 15, 16, and 20 of the southbound direction under CTSP and ETSP control are coincident (solid lines), but the trajectories of Requests 11, 12, 17, 18, and 19 are the same dotted line under ETSP control, which differ from the trajectories under CTSP control.

Compared with CTSP, the proposed ETSP model saved a total of 67 s of ineffective priority time (ranging from 4 to 11 s saved) (Table 4). Moreover, the total travel time of each bus under CTSP was the same as under ETSP, and less than the bus travel time under NTSP. Therefore, the proposed model outperforms CTSP in terms of effective and efficient priority time. The reduction of ineffective priority time decreased the adverse impacts of bus priority treatments on general traffic because fewer adjustments were made on the background signal plan and less green time was taken from nonpriority phases. These findings were further validated by simulation results, as described in the next section.

Simulation-Based Analysis

VISSIM simulation software was used to simulate the stochastic variation of traffic and transit flow and to evaluate the performance of the proposed method. VISSIM is a microscopic, time step– and behavior-based simulation model developed to model urban traffic and public transit operations (*29*). The process starts with VISSIM's component object model interface. This external module enables communication and dynamic object creation between the simulation environment and external processes, and the proposed method can be connected with VISSIM exactly. Measures of effectiveness including travel time and vehicle delay can be obtained from VISSIM. Each simulation runs for 1 h; to overcome the stochastic nature of simulation results, an average of 10 simulation runs was used.

To investigate the impacts on buses of the transit priority signal timings generated by the proposed model, the average travel times of buses under different demand scenarios were compared (Figure 6). Under both low- and high-transit-demand scenarios, the proposed model achieved the TSP objective compared with NTSP, as reflected by reduced bus travel time. Compared with NTSP, more than 11.2% and 13.1% reductions in total travel time were gained under the low-transit-demand scenario and high-transit-demand

TABLE 3 Background Signal Timings

GT Demand Scenario	Intersection	Cycle Length (s)	Duration of Green Time (s) Phase 1	Phase 2	Phase 3	Phase 4
Low	1	83	19	16	25	11
	2	83	56	na	19	na
	3	83	56	na	19	na
	4	83	19	16	25	11
Medium	1	97	23	19	30	13
	2	97	66	na	22	na
	3	97	66	na	22	na
	4	97	23	19	30	13
High	1	120	29	25	38	16
	2	120	83	na	28	na
	3	120	83	na	28	na
	4	120	29	25	38	16

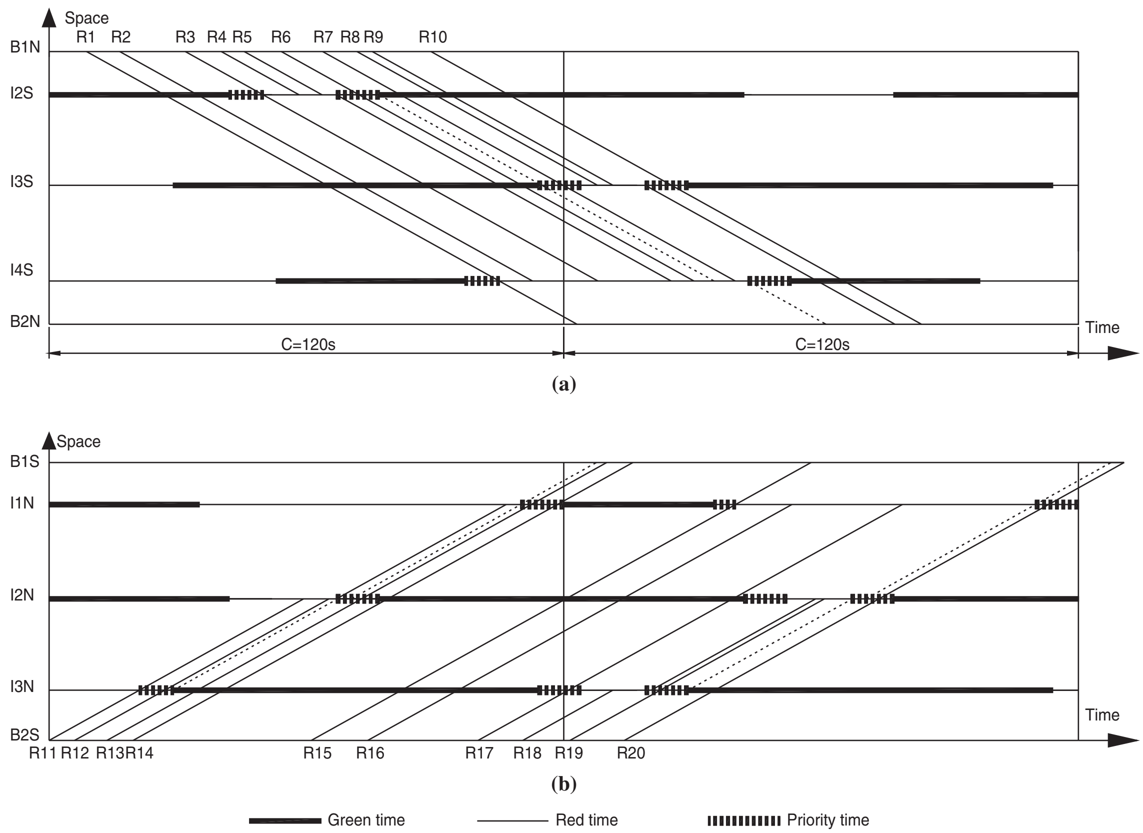
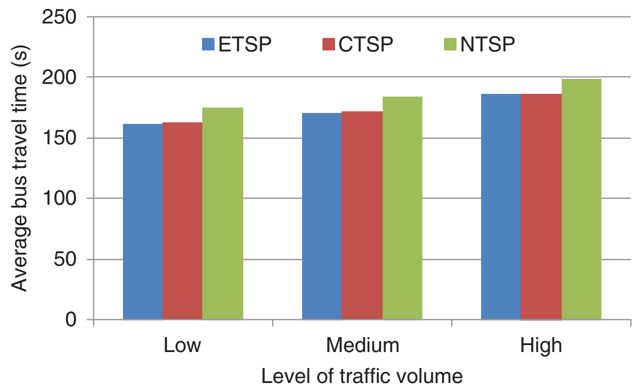


FIGURE 5 Trajectory of priority requests (projected into one cycle): (*a*) northbound priority treatments and (*b*) southbound priority treatments.

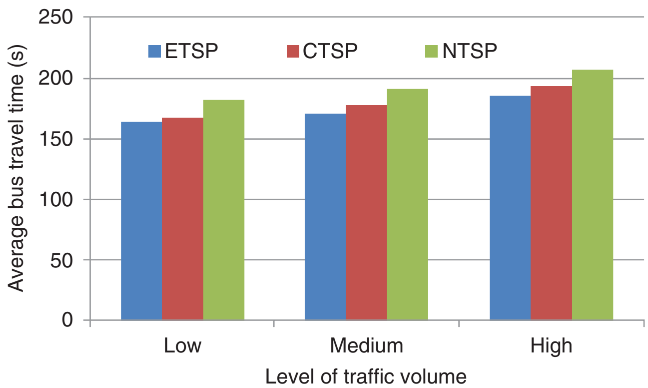
TABLE 4 Reduction of Travel Time and Ineffective Priority Time

Priority Request	CTSP (s)						ETSP (s)						Ineffective Priority Time (s)	ETSP–CTSP Travel Time (s)	NTSP Travel Time (s)
	I1		I2		I3		I1		I2		I3				
	GE	RT	GE	RT	GE	RT	GE	RT	GE	RT	GE	RT			
NBR01	na	na	na	na	8	na	na	na	na	na	8	na	0	114.4	182.4
NBR02	na	na	na	na	na	10	na	na	na	na	na	10	0	164.7	174.7
NBR03	8	na	na	na	na	10	na	na	1	na	na	10	7	149.4	159.4
NBR04	na	10	na	na	na	10	na	na	1	na	na	10	9	141	151
NBR05	na	10	na	na	na	10	na	na	1	na	na	10	9	135.6	145.6
NBR06	na	5	na	na	na	10	na	na	1	na	na	10	4	127	137
NBR07	na	na	6	na	na	10	na	na	6	na	na	10	0	117.4	143.5
NBR08	na	na	na	10	na	na	na	na	10	na	na	na	0	125.5	135.5
NBR09	na	na	na	10	na	na	na	na	10	na	na	na	0	121.9	131.9
NBR10	na	na	na	4	na	na	na	na	4	na	na	na	0	109.5	118.2
SBR11	na	8	na	10	na	10	na	na	na	7	na	10	11	127.6	137.6
SBR12	na	2	na	10	na	10	na	na	na	7	na	10	5	121.7	131.7
SBR13	na	na	na	4	na	8	na	na	na	4	na	8	0	116.5	124.2
SBR14	na	na	na	na	na	2	na	na	na	na	na	2	0	116.5	118
SBR15	na	na	na	na	5	na	na	na	na	na	5	na	0	116.5	196.5
SBR16	na	na	na	na	na	10	na	na	na	na	10	na	0	173.3	183.3
SBR17	7	na	na	na	na	10	na	na	na	na	na	10	7	147.6	157.6
SBR18	na	10	na	10	na	10	na	na	na	na	na	10	14	137.1	147.2
SBR19	na	7	na	10	na	10	na	na	na	na	na	10	11	126.2	136.2
SBR20	na	na	na	4	na	7	na	na	na	4	na	7	0	116.5	123.5

NOTE: GE = green extension; RT = red truncation; NBR = northbound request; SBR = southbound request.



(a)



(b)

FIGURE 6 Average travel time of buses under (*a*) low and (*b*) high transit demand.

scenario, respectively. The proposed model outperformed CTSP in that all scenarios produced less bus travel time. Compared with CTSP, more significant travel time decreases were achieved under the high-transit-demand scenario (range, 7.2% to 12.2%) than under the low-transit-demand scenario (range, 2.6% to 4.1%). This difference is related to the fact that the proposed model minimizes not only the total travel time but also the total waste time. This combined minimization results in the reduction of ineffective priority adjustments on the background signal timings and an increase in the number of cycles that can be used to provide effective priority.

The findings described above were further validated by the bus priority service ratio, which is the ratio of number of buses served by priority strategy to the total number of priority requests (Table 5). The proposed ETSP method outperformed CTSP in that all scenarios produced a higher bus priority service ratio. Although the overall bus priority service ratios under the control of both CTSP and ETSP were lower under the high-transit-demand scenario than under the low-transit-demand scenario, the achievement of ETSP in increasing the bus priority service ratio under the high-transit-demand situation (more than 20%) was more significant than under the low-transit-demand situation (no more than 4%). This result occurred because the proposed model used fewer numbers of cycles in which only effective priority treatment was implemented for providing priority for the same number of buses, and the saved cycles were used to provide priority for more priority requests. Compared with the low-transit-demand scenario, under the high-transit-demand scenario more buses are in need of priority, and the advantages of ETSP can be fully used.

To investigate the impacts of the transit priority signal timings generated by the proposed model on general traffic, this study compared the average delay of general traffic of each intersection approach under the different demand scenarios (Figures 7 and 8). For traffic along the arterial, the ETSP model outperformed NTSP (all eastbound and westbound approaches experienced less delay time) because of its effective priority control strategies, which provide more green time for traffic along the arterial. For side streets, the proposed ETSP model's performance was also comparable to that of NTSP because the objective of both types of control is to provide priority for buses, which causes longer wait times on the side streets.

Under both the low- and high-transit-demand scenarios, the proposed ETSP model generated much less impact on regular traffic than CTSP because the delay of all approaches under ETSP control was closer to the traffic delay under NTSP control than to the delay under CTSP control. From Table 5 and Figures 6 and 7, one can conclude that ETSP provided better TSP for buses, with less impact on general traffic, than CTSP.

CONCLUSION

This paper presents a new coordinated TSP approach that can provide effective coordinated priority control for transit requests while minimizing ineffective priority time. The coordinated intersection group between two successive bus stops is defined as the basic control unit, and buses are detected after leaving the upstream stop, before arriving at the first intersection of the control unit. A linear program model was developed to generate the optimal effective and coordinated priority strategies to reduce bus travel time when bus priority is used. Case study results validated the effectiveness of the

TABLE 5 Bus Priority Service Ratio Under Different Scenarios

		Bus Priority Service Ratio					
Transit Demand	Control Type	Low GT	Improvement over CTSP (%)	Medium GT	Improvement over CTSP (%)	High GT	Improvement over CTSP (%)
High	ETSP	0.84	20.4	0.83	20.8	0.81	21.3
	CTSP	0.70	na	0.69	na	0.67	na
Low	ETSP	0.97	3.5	0.93	3.7	0.90	3.8
	CTSP	0.93	na	0.90	na	0.87	na

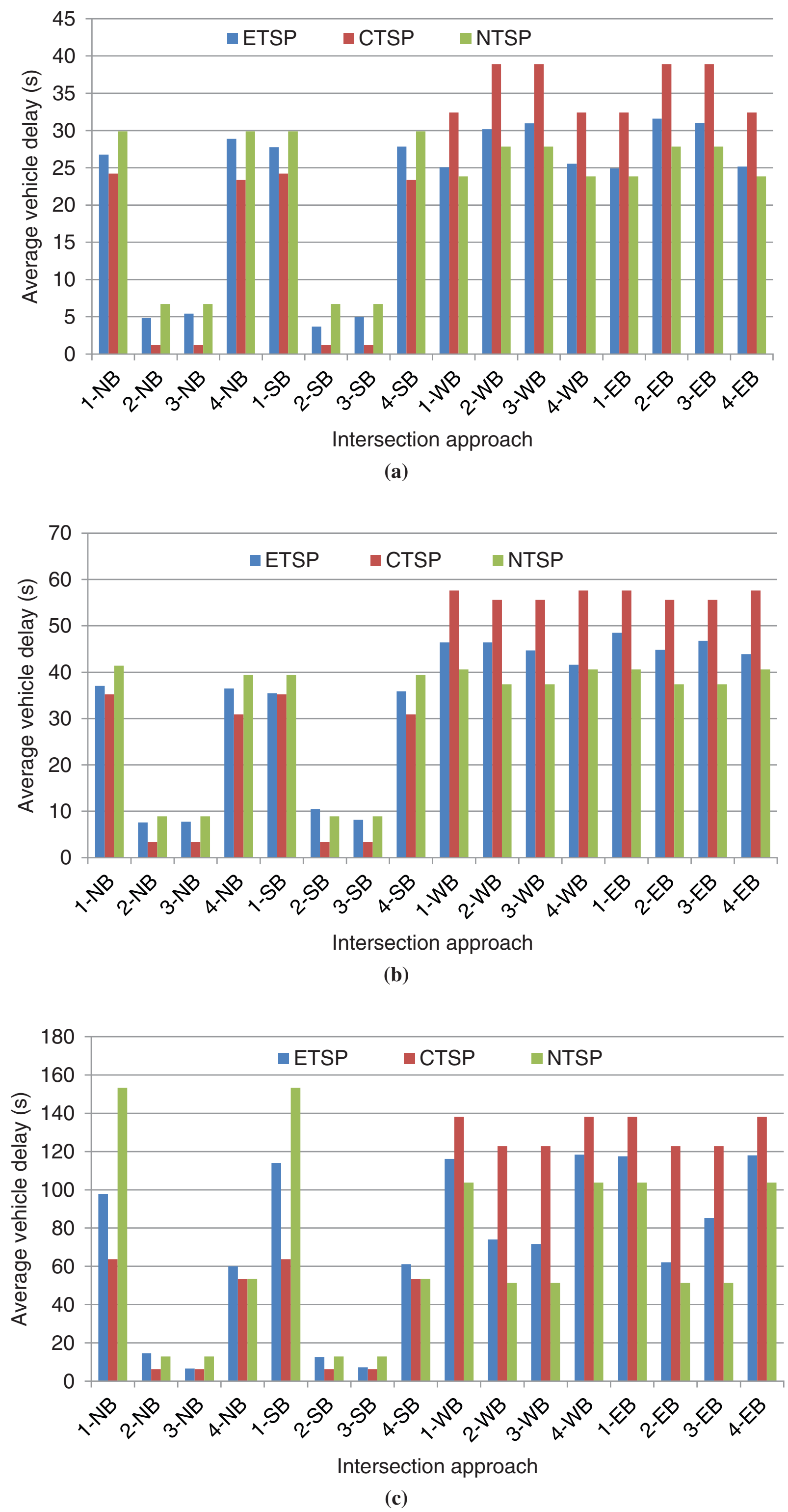


FIGURE 7 Average vehicle delay under low transit demand and (*a*) low, (*b*) medium, and (*c*) high general-traffic demand.

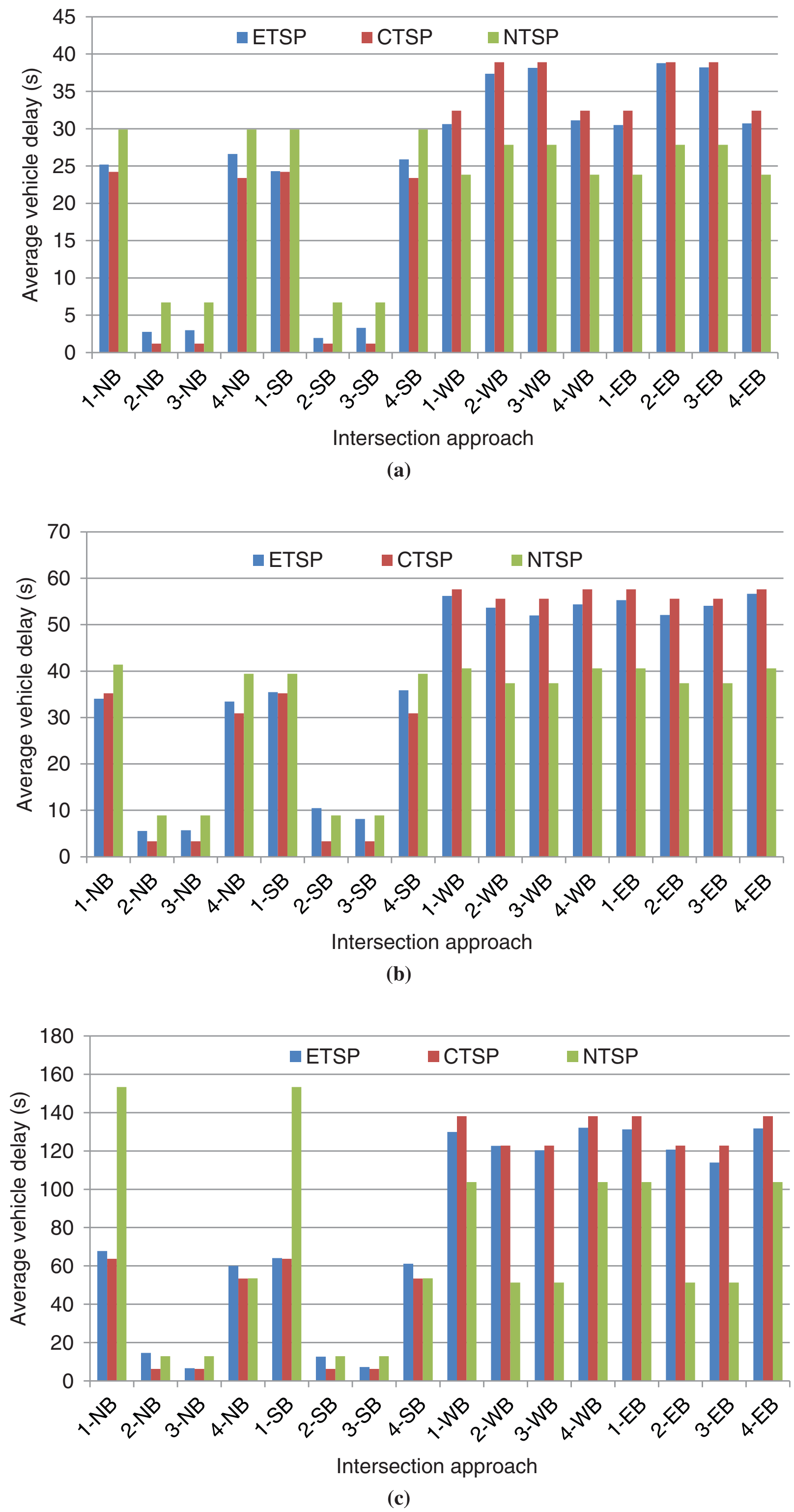


FIGURE 8 Average vehicle delay under high transit demand and (*a*) low, (*b*) medium, and (*c*) high general-traffic demand.

proposed model in comparison with the conventional TSP method and the no-signal-priority scenario under different traffic demand patterns.

In the future, more extensive numerical experiments or field tests will be conducted to assess the effectiveness of the proposed model under various demand patterns, turning movements, location of bus stops, distance between bus stop and stop line, and geometry configurations. Another possible extension is to develop a more accurate bus delay model and consider the stochastic impacts of bus speed and bus queue at intersections in the bus delay model.

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