Transit Priority Strategies for Multiple Routes Under Headway-Based Operations

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This paper presents a transit signal priority (TSP) model designed to consider the benefits both to bus riders and to intersection passenger car users. The proposed strategy, which is mainly for headway-based bus operations, offers the responsible agency a reliable way to determine the optimal green extension or red truncation duration in response to multiple bus priority requests from different routes. The control objective is to minimize bus passenger waiting time at the downstream bus stop while ensuring that the delays for all passengers are not increased. In tests that used field data from Jinan, China, the proposed strategy showed promise in reducing bus passenger waiting time and total intersection delay. Further exploration with simulation experiments for sensitivity analysis found that TSP is most effective if the ratio between bus and passenger volumes exceeds a threshold of 2%.

Hounsell and Shrestha reported that in response to different levels of passenger demand, transit agencies often divide their operating strategies into two groups: schedule-based service normally used for low-demand routes, and headway-based operations appropriate for high-demand corridors (*1*). With either strategy, transit signal priority (TSP) has long been recognized as a promising method for improving transit service reliability (*2*). Depending on the information available on the in-route bus and the functions of signal controllers, a variety of TSP controls can be implemented in practice. However, maximizing TSP effectiveness remains a challenging issue.

Wilbur Smith and Associates et al. were among the first to conduct bus preemption experiments to reduce bus travel time (*3*). Yagar and Han proposed some unconditional priority strategies for buses (*4*). Researchers later developed conditional priority strategies to improve bus punctuality that were based on priority rules and the target bus's performance with respect to its schedule; these strategies assumed that bus-associated information was available from an automatic vehicle location system or real-time bus operation management (*5–7*). Depending on the TSP focus, operating agencies may select different control objectives to improve their service reliability. For example, Head et al. (*8*) and Ma et al. (*9*) proposed a control objective of minimizing the total delay for all detected buses. Mirchandani et al. (*10*), Christofa and Skabardonis (*11*), and Li et al. (*12*) extended the objectives to reduce the total vehicle delay of buses and passenger cars. Chang et al. (*13*), Vasudevan (*14*), and Wu et al. (*15*) selected the total person delay of buses and passenger cars as the control objective. Chang et al. (*16*) and Kleoniki et al. (*17*) have conducted extensive simulation experiments to compare the performance of various TSP models. Seward and Taube (*18*) and Abdy and Hellinga (*19*) also presented several mathematical methods to evaluate the performance of TSP control strategies.

Unlike schedule-based TSP research, very little research on headway-based methods has been reported in the literature. Hounsell et al. introduced a method to grant bus priority according to the headway between the current bus and the last preceding bus (*5*). Ling and Shalaby used reinforcement learning that was based on the bus headway deviation from its schedule to determine the best duration of an extended signal phase; they used Paramics software for simulation and evaluation (*6*). Hounsell et al. reported the operations of bus signal priority within iBUS in London and explored the effects of global positioning system locational errors on bus priority benefits (*7*). Altun and Furth presented a combination method, including bus holding at a stop and conditional signal priority to late buses, to make buses operate under a uniform headway (*20*). Hounsell and Shrestha recently presented a new approach to grant bus priority for a headway-based service (*1*). The key logic of their method is to grant a bus priority if its forward headway is longer than the backward headway.

Despite the potential effectiveness of Hounsell and Shrestha's method, its potential application to a congested intersection that may receive multiple transit priority requests during the same cycle needs some enhancements. For example, Figure 1 displays the distribution of headways of bus Route 35 in Jinan, China, collected on March 26, 2012. As shown in Figure 1*a*, the scheduled headway remained unchanged within the initial time period (e.g., from 14:24 to 16:32). However, as a result of traffic congestion and intersection delays, the detected actual headways began to vary with distance and time. Figure 1*b,* which shows the absolute headway deviation at the third, seventh, and 10th stops of Route 35 at different times of the same day, reveals an increasing deviation of headways along the route, especially during the peak hour periods (i.e., 6:00 to 10:00 and 18:00 to 20:00). Because different buses experience different levels of headway deviation, granting signal priority to multiple bus requests while considering the potential impacts on both bus riders and passenger car drivers is a complex issue.

To contribute to headway-based TSP research, this study addressed a scenario in which a signalized intersection controller needs to determine how to grant transit priority when various buses from different routes are ahead or behind schedule. The conventional first-come, first-served strategy may improve the schedule reliability of some buses, but it does so at the cost of others; that is, such a strategy may reduce the headway between buses that are either on

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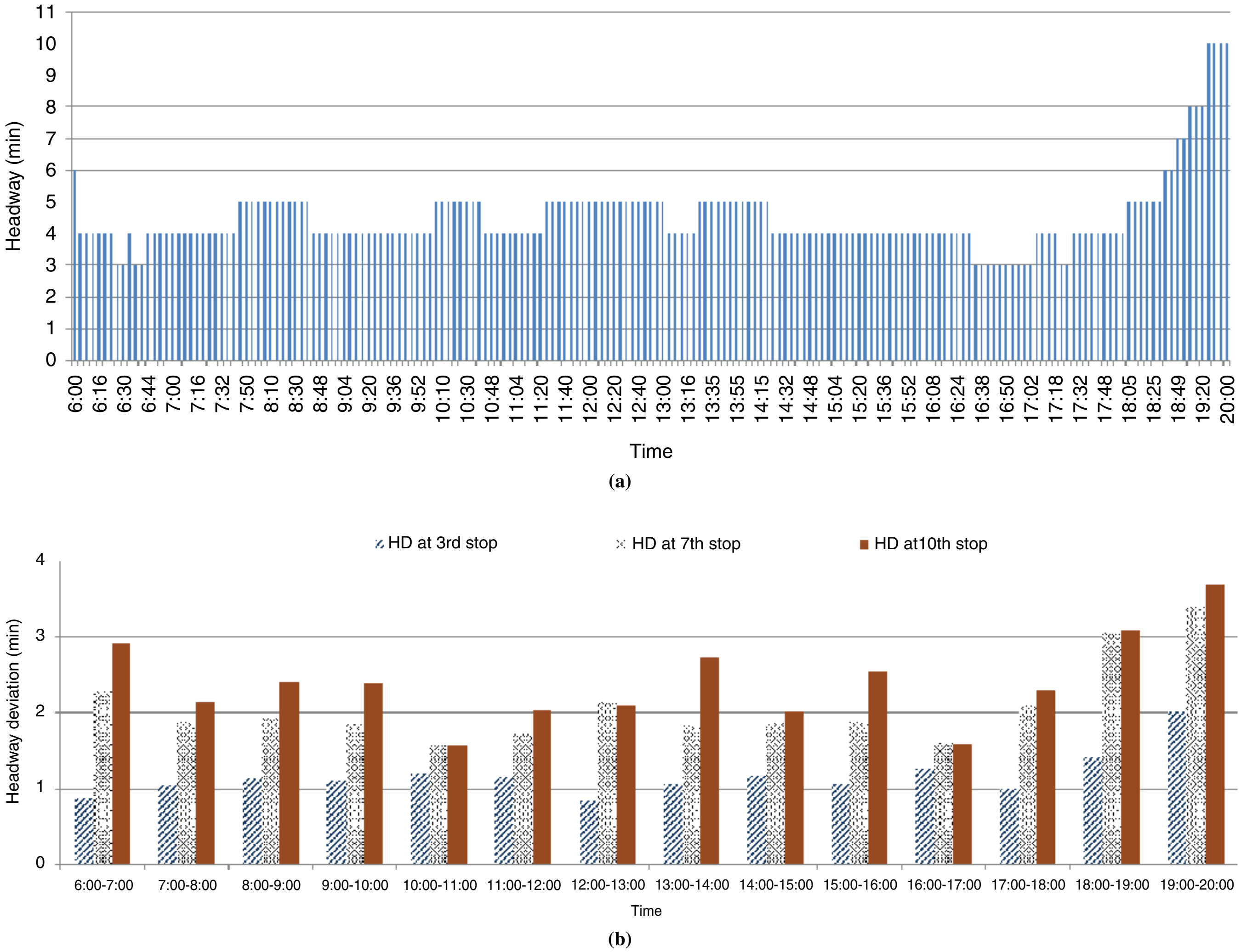

FIGURE 1 Distribution of (*a*) scheduled headway and (*b*) absolute headway deviation on bus Route 35 in Jinan.

their scheduled headways or even ahead of the required arrival time at the next stop. Depending on the sequence of buses from different routes and their deviations from scheduled headways, the intersection controller needs a rigorous logic to determine the length of green extension or red truncation for multiple priority requests in order to minimize the waiting time of passengers at the next stop over the control period. More specifically, the objectives of this study were to

- Design a control system based on various measures of effectiveness to handle multiple priority requests from buses on different routes and
- Identify critical factors or relationships that may affect TSP efficiency under different traffic conditions.

This paper is organized as follows: the next section describes the basic problem, and the third section develops a model of headway-based TSP control to improve bus reliability service. The case study in the fourth section demonstrates the model application with field data from the city of Jinan. Sensitivity analysis and conclusions are presented in the fifth and sixth sections, respectively.

DESCRIPTION OF PROBLEM

Assuming a small scheduled headway and randomly arriving passengers along a bus route, Kulash indicated that the average passenger waiting time can be estimated with Equation 1 (*21*):

$$E(w) = \frac{E(H)}{2} + \frac{\text{var}(H)}{2E(H)} \tag{1}$$

where

$E(w)$ = expected waiting time per passenger,
$E(H)$ = mean headway, and
$\text{var}(H)$ = variance of the headway distribution.

Hence, under a fixed-headway operating system, one potentially effective way to reduce the average passenger waiting time is to control or minimize the headway variance of all buses on the same route. To do so, Hounsell and Shrestha proposed a headway adjustment rule for a route operation that concurrently considers three adjacent buses (the current bus, the forward bus, and the backward bus) (*1*).

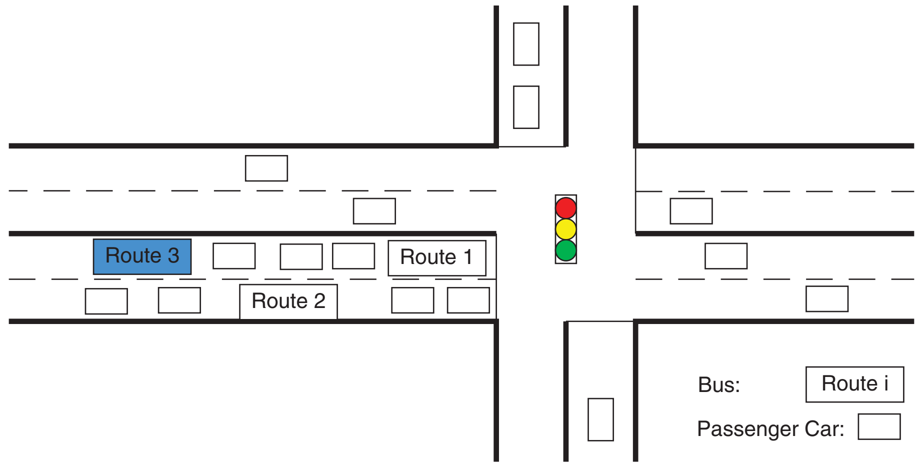

FIGURE 2 Impacts of bus sequences over different routes at a TSP-controlled intersection.

Their proposed rule grants a priority to the bus behind its schedule on the basis of the headway between the current bus and the last preceding bus. In their model, the approaching bus will be given a priority if its forward headway is larger than the backward headway. However, for a multiroute scenario, the decision to grant a priority involves more complex issues. Figure 2 illustrates a scenario in which multiple buses from different routes are approaching a TSP-controlled intersection. Their arrival sequence at the target intersection may create a dilemma for the TSP control system. For example, the Route 3 bus is behind schedule, but the Route 1 and Route 2 buses are ahead of schedule. According to the exiting control principle, a priority should be provided to the Route 3 bus, but not to the Route 1 and Route 2 buses. However, a priority to Route 3 bus will inevitably force the Route 1 and Route 2 buses, called priority-driven buses, to pass through the intersection, which may degrade the service reliability of these two bus routes.

Note that a priority provided to the major road will certainly increase the delay of vehicles on the cross street. Thus, how to properly make a priority decision on the basis of the overall system benefits becomes an important issue for TSP operations. The model presented was developed to address this issue.

MODEL DEVELOPMENT

The goal of the proposed control system is to use the TSP control to reduce bus headway variance and consequently minimize the total passenger waiting time at the next bus stops. Most conventional TSP controls provide a fixed bus-priority time (i.e., 15 s) for green extension or red truncation. Recent technological advances, however, enable TSPs to provide varying priority times, which promises to alleviate the controller's dilemma with the multiple-route priority control scenario.

Figure 3 illustrates the control structure of the proposed system, in which the control module will be activated to process a priority decision at the end of a green phase according to the location and sequence of all detected buses. In Figure 3, the variable t^R represents the communication time among bus vehicles, signal controllers, and the control center; t^C is the reaction time of signal controllers. The decision outcome will be the number of buses granted priority and the required duration for green extension or red truncation.

The control module is designed to make the priority decision on the basis of the available data. The model assumes that the locations of all buses are available via the Global Positioning System or automatic vehicle location systems and that the signal controller is able to provide varying priority times. The entire decision-making process for the TSP control module in response to multiple requests includes the following steps:

Step 1

Collect bus location data and current signal settings from the available communication system.

Step 2

Estimate the maximal allowable duration for green extension or red truncation in terms of traffic conditions.

To limit the impact of the priority on nonpriority traffic volumes, the maximum allowed priority time is determined by the current volume-to-capacity (v/c) ratio on the cross street, as shown by Equation 2:

$$\frac{(\mathrm{v/c}) \cdot t^{g}_{p,q}}{t^{g}_{p,q} - t^{\mathrm{gr}}_{p,q}} \leq \beta \qquad (2)$$

where

$t^{g}_{p,q}$ = green duration of nonpriority phase p in cycle q without priority,
$t^{\mathrm{gr}}_{p,q}$ = green reduction in nonpriority intersection approach caused by priority extension, and
β = maximum allowed v/c ratio on the cross street after priority.

The minimum green time is set as shown by Equation 3 to ensure pedestrian safety:

$$t^{g}_{p,q} - t^{\mathrm{gr}}_{p,q} > t^{\min} \qquad \forall p, q \qquad (3)$$

where $t^{\min}$ is the minimal green duration of the nonpriority phase.

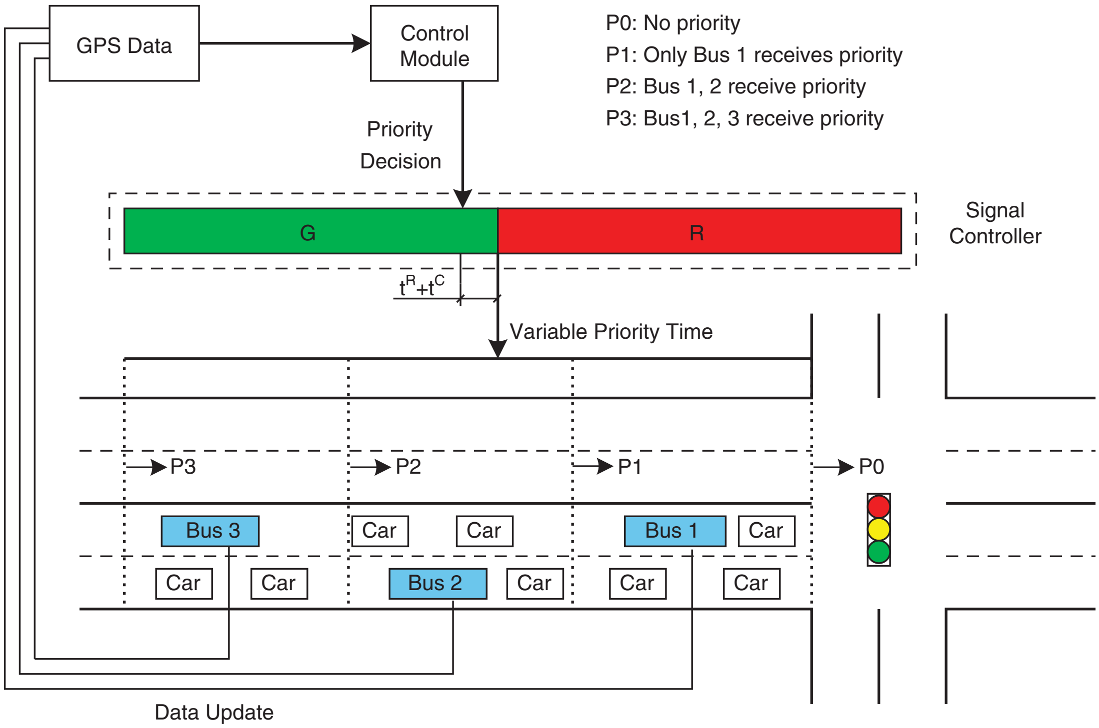

FIGURE 3 Signal control logic of proposed TSP system.

Step 3

Detect the approaching buses and their current locations a few seconds (the sum of communication time t^C and reaction time t^R plus the maximal allowable duration) before the end of a green phase.

Step 4

Estimate the potential benefits of granting a priority to a different number of detected buses.

The purpose of this step is to estimate the resulting benefits if a priority of green extension or red truncation for a specified length is granted to the major route. Depending on the selected criterion, one can estimate the delay from the perspective of the transit users, passenger car users, or the total social benefits of roadway users. As the focus of TSP control is to minimize the headway variance of each bus route, the first step to develop the control logic is to compute the resulting headway of each bus, given the current bus locations, if granted a priority.

Step 4.1

Calculate the headway of each detected bus under an intended green extension or red truncation.

Assuming that both the forward and backward buses will keep their current driving conditions during the priority period, one can calculate the estimated headway for each bus after TSP control as shown in Equations 4 and 5:

$$h_{r,i}^{f'}(k) = h_{r,i}^{f}(k) + f_{r,i,p,q}(k)\,t_{r,i,p,q}^{\mathrm{SB}} \tag{4}$$

$$h_{r,i}^{b'}(k) = \max\left\{h_{r,i}^{b}(k) - f_{r,i,p,q}(k)\,t_{r,i,p,q}^{\mathrm{SB}},\, 0\right\} \tag{5}$$

where

$h_{r,i}^{f}(k)$ and $h_{r,i}^{b}(k)$ = actual forward and backward headways, respectively, of bus i on route r at stop k before receiving signal priority;

$t_{r,i,p,q}^{\mathrm{SB}}$ = time savings of bus receiving priority at phase p of cycle q; and

$f_{r,i,p,q}(k)$ = set of binary variables representing priority status.

Equation 4 is formulated to reflect the fact that if the subject bus is stopped by a red signal, the actual headway to its forward bus will be increased (i.e., it will be longer than the target headway); otherwise, the actual headway will remain unchanged. In other words, when a subject bus gets the priority and does not stop at the intersection, the headway will be unchanged. Equation 5 is constructed on the same notion.

Given a detected bus arrival sequence, the priority status of each bus can be expressed as shown by Equation 6:

$$f_{r,i,p,q}(k) = \begin{cases} 0 & t_{p,q}^{\mathrm{eg}} \geq \mathrm{et}_{r,i,p,q} \\ 1 & \text{otherwise} \end{cases} \tag{6}$$

where $\mathrm{et}_{r,i,p,q}$ is the required extra green time for bus i to pass the intersection at the end of a green phase and $t_{p,q}^{\mathrm{eg}}$ denotes the additional green durations for all detected buses, which need to be optimized. If $f_{r,i,p,q}(k)$ is equal to zero, then bus i gets the priority. Single-bus priority and multiple-bus priority are distinguished by $\mathrm{et}_{r,i,p,q}$ and $t_{p,q}^{\mathrm{eg}}$, respectively.

The time savings of each bus receiving a priority status can be computed by Equation 7:

$$t^{\mathrm{SB}}_{r,i,p,q} = \begin{cases} t^{r}_{p,q} - \mathrm{et}_{r,i,p,q} & \text{if priority strategy is green extension} \\ \mathrm{et}_{r,i,p,q} & \text{if priority strategy is red truncation} \end{cases} \quad (7)$$

where $t^{r}_{p,q}$ is the red time of phase p. The time savings by a green extension is generally much larger than with a red truncation when the bus volume exceeds 60 vehicles/h (*22*).

Step 4.2

Estimate the average passenger waiting time at bus stops.

The second task at this decision step is to compute the average waiting time of passengers for each route with and without receiving signal priority, which can be calculated with Equation 8:

$$\alpha_{r,i}(k) = \begin{cases} \dfrac{\left(h^{f'}_{r,i}(k)\right)^2 + \left(h^{b'}_{r,i}(k)\right)^2}{2\left(h^{f'}_{r,i}(k) + h^{b'}_{r,i}(k)\right)} & \text{if } h^{f'}_{r,i}(k) > \theta_r \text{, and } h^{b'}_{r,i}(k) > \theta_r \\ N + \dfrac{h^{b'}_{r,i}(k)}{2} & \text{if } h^{f'}_{r,i}(k) \le \theta_r \text{, and } h^{b'}_{r,i}(k) > \theta_r \\ N + \dfrac{h^{f'}_{r,i}(k)}{2} & \text{if } h^{f'}_{r,i}(k) > \theta_r \text{, and } h^{b'}_{r,i}(k) \le \theta_r \\ 2N & \text{if } h^{f'}_{r,i}(k) \le \theta_r \text{, and } h^{b'}_{r,i}(k) \le \theta_r \end{cases} \quad (8)$$

where

$\alpha_{r,i}(k)$ = average waiting time of passengers for each route,
θ_r = threshold to determine if bus bunching for each route exists, and
N = positive constant for the resulting penalty.

The total passenger waiting time for different routes at the next stop can be expressed by Equation 9:

$$c(k) = \sum_{r \in R_{p,q}} \beta_r \sum_{i \in I_{r,p,q}} c_{r,i,k} \alpha_{r,i}(k) \quad (9)$$

where

$R_{p,q}$ = set of detected bus route,
$I_{r,p,q}$ = set of detected bus vehicles,
β_r = weighted factor of each route, and
$c_{r,i,k}$ = number of passengers from bus i when bus arrives at stop k.

Step 4.3

Compute the delay reduction for bus passengers and passenger car drivers in the target arterial segment.

Assuming that the arrival rate of passenger cars to the TSP intersection is uniformly distributed when these buses are granted a priority, the total person delay reduction in the arterial can be approximated by Equation 10:

$$t^{\mathrm{SPC}}_{r,i,p,q} = \begin{cases} \dfrac{t^{r}_{p,q} - t^{\mathrm{eg}}_{p,q}}{2} & \text{if priority strategy is green extension} \\ \dfrac{t^{\mathrm{eg}}_{p,q}}{2} & \text{if priority strategy is red truncation} \end{cases} \quad (10)$$

Thus, the total person delay reduction for passenger cars on the arterial when receiving priority with transit vehicles can be shown as by Equation 11:

$$d^{\mathrm{PC}}_{R} = \mathrm{TV}^{\mathrm{PC}} n^{\mathrm{PC}} t^{\mathrm{SPC}}_{r,i,p,q} q^{\mathrm{PC}}_{p,q} \quad (11)$$

where

$\mathrm{TV}^{\mathrm{PC}}$ = time value of passenger car drivers,
n^{PC} = average number of persons per passenger car, and
$q^{\mathrm{PC}}_{p,q}$ = estimated queue of passenger cars. $q^{\mathrm{PC}}_{p,q}$ can be estimated with the model proposed by Chang et al. (*13*).

The person delay reduction of bus passengers with a priority signal is calculated with Equation 12:

$$d^{B}_{R} = \sum_{r \in R_{p,q}} \mathrm{TV}^{B} n^{B}_{r,i}(k) t^{\mathrm{SB}}_{r,i,p,q} f_{r,i,p,q}(k) \quad (12)$$

where TV^{B} is the unit time value of bus passengers and $n^{B}_{r,i}(k)$ is the average number of on-board bus passengers.

Step 4.4

Estimate the increased delay for passenger car riders on the cross street.

Granting a priority to buses in the arterial will inevitably reduce the green time on the cross street, which will consequently cause extra delay for cross-street vehicles. The computation of the extra delay is based on two separate parts: one is the increased delay of those initial queuing vehicles as a result of the reduction of green time; the other is the extra delay of these vehicles approaching the intersection during the TSP execution period. The average delay per queuing vehicle can be expressed by Equation 13*a*:

$$t^{\mathrm{WPC1}}_{r,i,p,q} = \begin{cases} t^{\mathrm{eg}}_{p,q} & \text{if priority strategy is green extension} \\ t^{r}_{p,q} + t^{\mathrm{eg}}_{p,q} & \text{if priority strategy is red truncation} \end{cases} \quad (13a)$$

With the assumptions that vehicles arriving at the cross street during the TSP execution period follow a uniform distribution and each cycle can clear the queue at the cross street, the average delay per approaching vehicle can be calculated by using Equation 13*b*:

$$t^{\mathrm{WPC2}}_{r,i,p,q} = \begin{cases} \dfrac{t^{\mathrm{eg}}_{p,q}}{2} & \text{if priority strategy is green extension} \\ t^{r}_{p,q} + t^{\mathrm{eg}}_{p,q} & \text{if priority strategy is red truncation} \end{cases} \quad (13b)$$

Hence, one can approximate the increased person delay for passenger cars on the cross street with Equation 14:

$$d_I^{PC} = TV^{PC} n^{PC} \left(q_{p,q}^{PC1} t_{r,i,p,q}^{WPC1} + q_{p,q}^{PC2} t_{r,i,p,q}^{WPC2} \right) \quad (14)$$

where $q_{p,q}^{PC1}$ and $q_{p,q}^{PC2}$ denote the queue estimation of queuing or approaching vehicles, respectively, which can be estimated with the model proposed by Chang et al. (*13*).

By using Equations 9, 11, 12, and 14, one can calculate the total person delay reduction for on-board bus riders, those waiting at the downstream bus stop, and those passenger vehicle users at the target intersection during the TSP execution period if given a priority green extension or red truncation for $t_{p,q}^{eg}$ seconds, as shown by Equation 15:

$$D = d_R^{PC} - d_I^{PC} + d_R^{B} + c(k) - c^{NON}(k) \quad (15)$$

where $c^{NON}(k)$ is the total passenger waiting time of all bus routes without priority. Bus passenger waiting time saving could be one of the major contributors to the total person delay reduction. Therefore, Equation 15 includes the passenger waiting time savings.

Step 5

Determine the priority strategies and the optimized green duration for the priority requests.

This system will grant a bus priority on the major road for an extended $t_{p,q}^{eg}$ green seconds, caused by green extension or red truncation, if the following criteria are satisfied:

1. To limit traffic disruptions on the cross street, a red truncation and green extension cannot be taken simultaneously in one signal cycle;
2. The total bus passenger waiting time will be reduced; and
3. The total person delay will not be increased by a TSP execution.

Step 6

Execute the TSP control strategy.

The final optimal decision would be sent to the local signal controller or control center to execute the TSP control, including the extended green duration for the priority phase and the green time reduction for the nonpriority approach.

CASE STUDY

Experimental Design

To illustrate the applicability and efficiency of the proposed system, this study used VISSIM as an unbiased tool for performance evaluation. The authors used the VISSIM-COM interface to develop a program to simulate bus operations and signal control logic with VB.NET and the MYSQL database. During the simulation, the program detects and records the real-time bus locations, automatically computes the time-varying headway of each bus for each route, and adjusts the signal timings according to the bus arrival sequence. Figure 4 shows the flow chart of the entire simulator and decision process for the proposed TSP operations. To search the optimal feasible solution efficiently, each candidate solution organized in the ascending order would be tested sequentially.

Wei'er Road in Jinan was selected as a test case to evaluate the effectiveness of the proposed decision process for bus signal priority (Figure 5). The section of interest is about 3 km long; however, to improve the accuracy of the simulation, about 4.5 km of Wei'er Road and its connected arterials were included in the simulation model. The key traffic pattern and geometric features in the simulation model are listed below:

- The total travel distance of bus routes is about 6.0 to 6.8 km;
- The 3-km study section of Wei'er Road has six two-way lanes;
- The v/c is about 0.7;

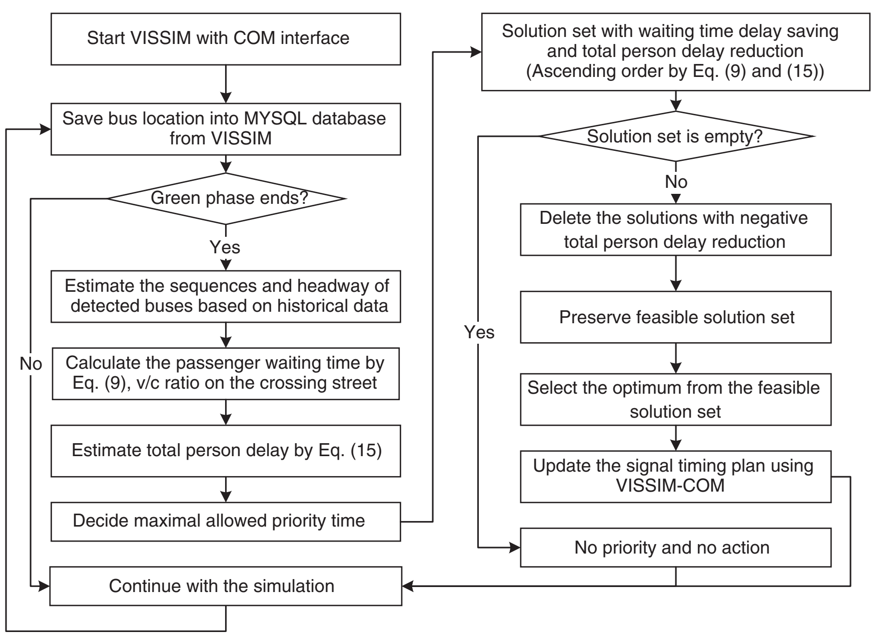

FIGURE 4 Flowchart of simulation evaluation.

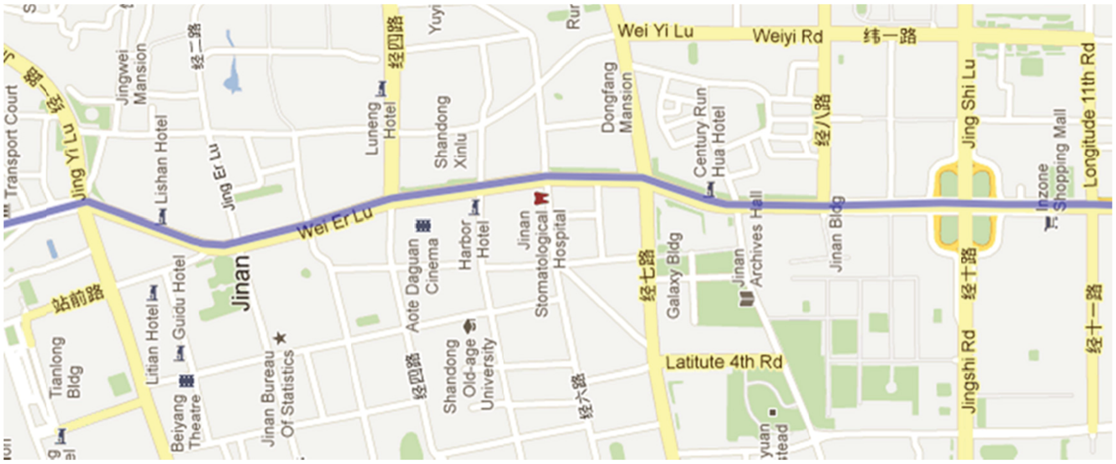

FIGURE 5 View of Wei'er Road in Jinan.

- The mean headway is about 4 min, and the variance observed on the target arterial ranges from 2 to 6 min;
- There are eight bus routes in two directions;
- No bus exclusive lane is available on the arterial;
- There are six intersections along the arterial, only two of which can offer bus priority;
- The duration of simulation time is about 3,600 s;
- The equivalent passenger number for buses and passenger cars is $n_{r,i}^{B}(k) = 20$ and $n^{PC} = 2$/vehicle, respectively;
- The threshold of bus bunching for each route is $\theta_r = 1.5$ min;
- The time value of bus passengers and passenger car users is $TV^B = 0.6$ and $TV^{PC} = 1.0$, respectively;
- The penalty for occurrence of bus bunching is $N = 10$ min; and
- The sum of communication time and reaction time $(t^C + t^R)$ is 3 s.

The threshold of bus bunching, the weighting factor of each bus, and values of time were obtained from the field survey; the penalty for occurrence of bus bunching was determined by increased waiting time according to historical data. The communication time and reaction time are discussed in the literature (*23*).

Experimental Results

For control efficiency and convenience of case illustration, this study only considered the TSP of green extension in the experimental analysis. The proposed strategy was evaluated with the following three scenarios:

Scenario 1. No priority control,
Scenario 2. Priority to all requested buses (15 s for green extension), and
Scenario 3. The proposed control with variable green extension.

Several measures of effectiveness were selected for model evaluation: headway variance, passenger waiting time, total bus passenger delay (including waiting time and travel delay), and total person delay of the entire network. Figure 6 compares the results among different scenarios. Some key findings are summarized below:

1. The proposed control in this study can outperform the other two methods in terms of reduction in bus headway variance (12.9%), passenger waiting time (4.8%), total bus passenger delay (about 6.7%), and total person delay of all vehicles (about 9.9%) (Figure 6).
2. Despite the lack of difference in average headways among the three methods, the variance of headways with the proposed strategy is far less than that under the other two methods (Figure 6*a*). The reductions in variance for Routes 2, 12, and 11 are up to 21.7%, 31.8%, and 44.9%, respectively, which is consistent with the reduction in the total passenger waiting time (Figure 6*b*). Furthermore, the probability of having bus bunching under the scenario of granting priority to all buses is 25% more than with the proposed strategy.
3. Because the proposed control method concurrently considers the impacts of signal priority on buses and passenger cars, it can also achieve a better performance than the other two methods with regard to reduction in bus passenger delay (Figure 6*c*). Note that bus passenger delay is the sum of increased passenger waiting time and travel time. The proposed TSP model can significantly reduce the average waiting time because in the priority-to-all-buses cases some on-time or early buses are forced to obtain priority, which inevitably increases the variance of bus headways and thus the average waiting time for passengers at the stops in the downstream link.
4. Figure 6*d* reveals that the proposed TSP strategy produces less total person delay for the entire arterial during the operational period compared with the priority-to-all-buses TSP. The latter method may cause significant impacts on cross-street traffic flows that could lead to a significant increase in the total vehicle delay.

SENSITIVITY ANALYSIS

To evaluate the reliability and effectiveness of the proposed strategy, the model's sensitivity was tested with respect to the following three key factors:

- The ratio between bus volume and total passenger car volume,
- Traffic volume at the arterial, and
- Traffic volume on the cross street.

A summary of key variables for each scenario is listed in Table 1.

As shown in Figure 7, regardless of the ratio between bus and traffic volumes, the proposed TSP strategy can always reduce the bus passenger delay (the sum of the waiting time and travel time delay).

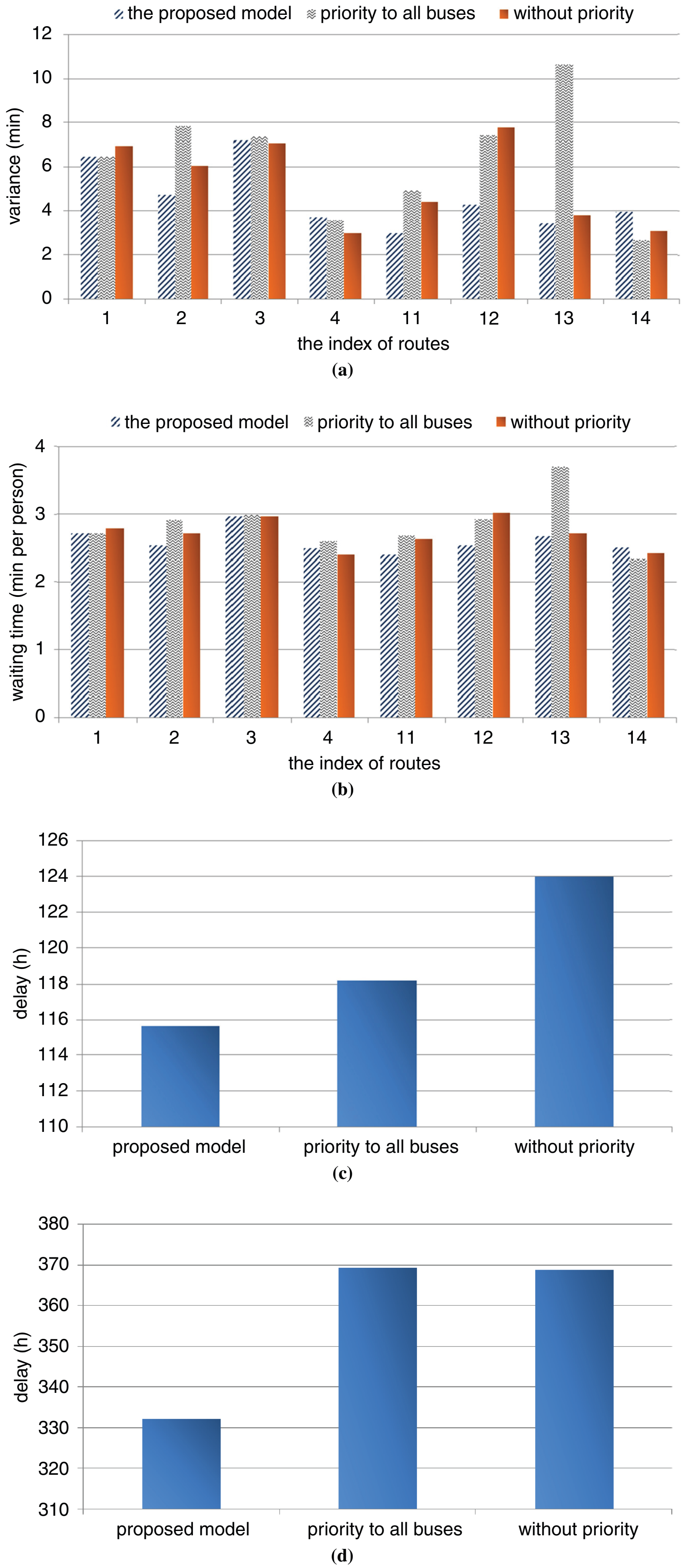

FIGURE 6 Comparisons of three TSP methods for (*a*) distribution of headway variance, (*b*) bus passenger waiting time, (*c*) total bus passenger delay, and (*d*) total person delay of the entire arterial.

TABLE 1 Detailed Descriptions of Scenarios A1–A8

Scenario	Traffic Volume at Priority Approach (vph)	Bus Ratio (%)	Traffic Volume on Crossing Street	Number of Bus Routes in Two Directions
A1	1,400	1	420	6
A2	2,400	1	720	6
A3	1,400	2	420	10
A4	2,400	2	720	10
A5	1,400	3	420	16
A6	2,400	3	720	16
A7	1,400	4	420	16
A8	2,400	4	720	16

NOTE: vph = vehicles per hour.

However, the proposed control strategy yields a more significant reduction in the total network person delay if the ratio between bus and total traffic volumes exceeds 2%; such benefits will increase with the total intersection traffic volume.

The comparison between different traffic volumes in the priority approach reveals that a larger delay reduction can be achieved with the proposed strategy under the scenario of having high traffic volume on the primary arterial and a high percentage of buses.

CONCLUSION

This paper presents a headway-based TSP control system for multiple bus requests from different routes. The proposed model aims to minimize the passenger waiting time at bus stops without causing excessive impacts to the cross street. The overlaps of multiple bus routes means that the conventional first-come, first-served strategy often fails to offer an efficient control because not every bus in the target link is behind schedule. The proposed model uses the variable priority-time technique, which is capable of performing a more precise control and can give partial priority to detected buses. To minimize the negative impact to the entire intersection, the proposed TSP strategy also computes the total person delay to ensure its efficiency.

The performance evaluation, which used field data from Jinan under a simulated platform, clearly shows that the proposed TSP control can significantly reduce the passenger waiting time in the scenario of having multiple priority requests from multiple transit routes. An extensive sensitivity analysis revealed that the proposed TSP can yield significant benefits to both bus passengers and all users in the system if the ratio between bus and traffic volumes exceeds 2%. Such benefits are generally expected to increase with total intersection volume.

Future research will address the following three issues: (*a*) how to grant signal priority while reducing the impacts on the downstream intersection (i.e., granting priority to a late bus will also release more passenger cars, which may lead to congestion at the downstream

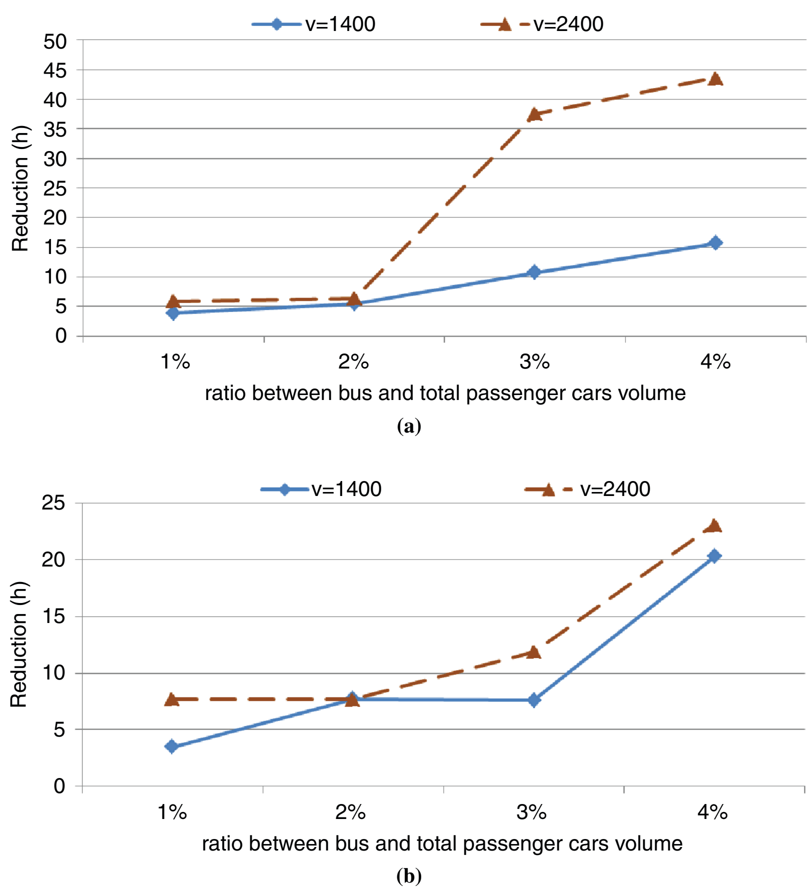

FIGURE 7 Comparisons of performance with and without priority: reduction in (*a*) bus passenger delay and (*b*) total person delay.

intersection, especially on coordinated arterials); (*b*) validation of the reliability and effectiveness of the TSP system under various geometric configurations and traffic demand patterns through more extensive experiments or field tests; and (*c*) design of a bus progression control system on urban arterials that is based on bus dwelling time at stops and global positioning system bus location data.

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