Transit Priority Strategies for Multiple Routes under Headway-based Operations

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ABSTRACT

This paper presents a transit signal priority (TSP) model designed to consider the benefits of both bus riders and all intersection passenger car users. The proposed strategy, 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. Using the field data from Jinan, China, the proposed strategy has shown its promise in reducing the bus passenger waiting time and the total intersection delay. Our further exploration with simulation experiments for sensitivity analysis has also found that TSP will be most effective if the ratio between bus and passenger volumes exceeds the threshold of 2 percent.

INTRODUCTION

In response to different levels of passenger demand, Hounsell and Shrestha *(1)* reported that 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. With either strategy, TSP has long been recognized as a promising method for improving transit service reliability (Abkowitz, et al. *(2)*). Depending on the information available on the in-route bus and the functions of signal controllers, there are a variety of TSP controls implemented in practice. However, how to properly use TSP so as to maximize its effectiveness remains a challenging issue.

In reviews of the literature for the schedule-based TSP control, it is noticeable that Wilbur *et al*. *(3)* first conducted bus preemption experiments to reduce bus travel time. Yagar and Han *(4)* proposed some unconditional priority strategies for buses. Some researchers later developed conditional priority strategies *(5-7)* to improve bus punctuality based on the priority rules and the target bus's performance with respect to its schedule, where bus associated information is assumed to be available from an Automatic Vehicle Location (AVL) system or a real-time Bus Operation Management (BOM) system. Depending on the focus of TSP, the 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. Furthermore, 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 Bruce *(19)* also presented several mathematical methods to evaluate the performance of TSP control strategies.

Different from the schedule-based TSP research, only very few headway-based methods have been reported in the literature. Among those, Hounsell *et al*. *(5)* introduced a method to grant bus priority based on the headway between the current bus and the last preceding bus. Ling and Shalaby *(6)* used reinforcement learning to determine the best duration of an extended signal phase based on the bus headway deviation from its schedule, and employed the Paramics software for simulation and evaluation. Hounsell *et al*. *(7)* reported the operations of bus signal priority within iBUS in London, and then explored the effects of GPS locational errors on bus priority benefits. Altun and Furth *(20)* presented a combination method, including bus-holding at a stop and conditional signal priority to late buses, to make buses operated under a uniform headway. Hounsell and Shrestha *(1)* recently presented a new approach to grant bus priority for a headway-based service. 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, collected on March 26, 2012 in Jinan, China. As shown in the graphical relation (see FIGURE 1(A)), the scheduled headway remains unchanged within the initial time period (e.g., from 14:24-16:32). However, due to the impact of traffic congestion and intersection delays, the detected actual headways begin to vary with distance and time. FIGURE 1(B) shows the absolute headway deviation at the 3th, 7th, and 10th stops of route 35 during different times of the same day, revealing an increasing deviation of headways along the route, especially during the peak-hour periods (i.e., 6:00-10:00; 18:00-20:00). Since different buses experienced different levels of headway deviation, how to grant the signal priority to multiple bus requests, considering the potential impacts on both bus riders and passenger car drivers, will thus be a complex issue.

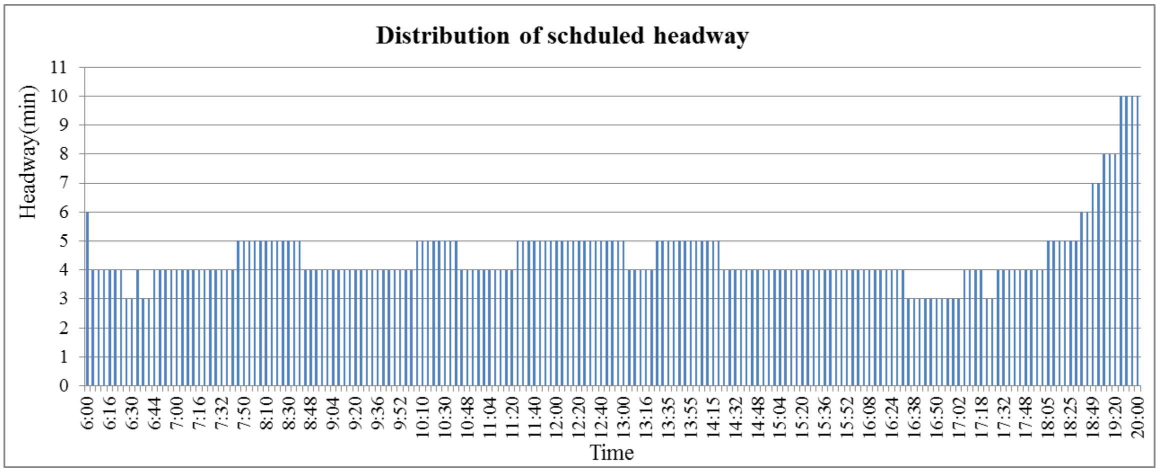

FIGURE 1(A) Distribution of scheduled headway

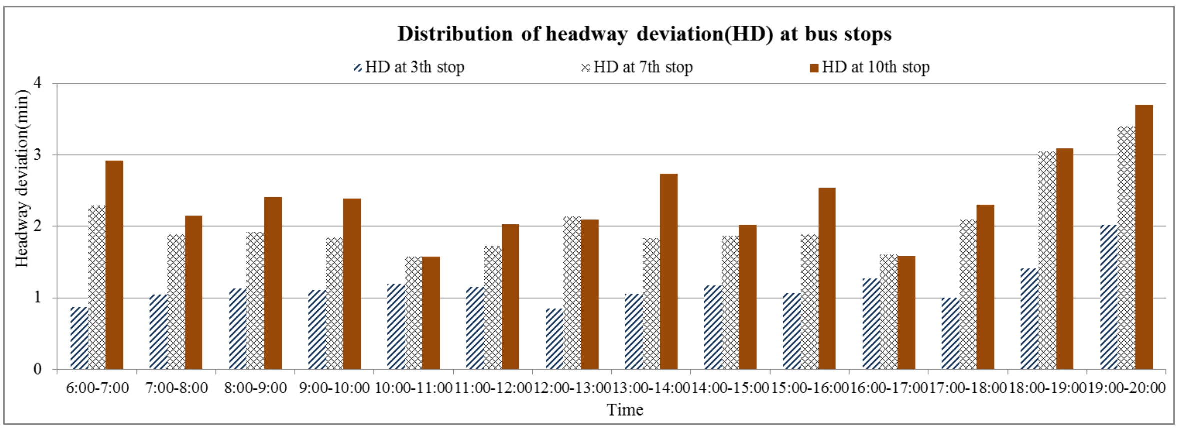

FIGURE 1(B) Distribution of absolute headway deviation

FIGURE 1 Headway distribution of route 35 in Jinan, China

Along the same line of headway-based research, this study intends to address the scenario where a signalized intersection needs to determine how to grant the transit priority strategy because some buses from different routes are ahead and some are behind their schedules. The conventional "first-come-first-served" (FCFS) strategy may improve the schedule reliability of some buses but at the cost of others, that is, to reduce the headway between some buses which are either on their scheduled headways or even ahead of the required arrival time at the next stop. Hence, depending on the sequence of buses from different routes and their deviations from scheduled headways, the intersection controller needs to have a rigorous logic to determine the length of green extension or red truncation for multiple priority requests so as to minimize the waiting time of passengers at the next stop over the control period. More specifically, the objectives of this study are to:

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

This paper is organized as follows: next section introduces the problem nature with field data from the city of Jinan, China. Section 3 illustrates a headway-based TSP control to improve bus reliability service. Section 4 demonstrates the model application with field data from China. Sensitivity analysis and conclusions are presented in Sections 5 and 6, respectively.

PROBLEM NATURE

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

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

where, $E(w)$ is the expected waiting time per passenger; $E(H)$ is the mean headway; and $Var(H)$ denotes the 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 *(1)* proposed a headway adjustment rule for a route operation by concurrently considering three adjacent buses (the current bus, the forward bus, and the backward bus). Their proposed rule will grant a priority to the bus behind its schedule based on 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 multi-route scenario, the decision to grant a priority involves some more complex issues. FIGURE 2 illustrates a scenario where multiple buses for different routes are approaching a TSP controlled intersection. Due to their arriving sequence to the target intersection, the TSP control system may face a “dilemma” for decision making. For example, Route-3 bus is behind of schedule while Route-1 and Route-2 buses are ahead of their schedules. According to the exiting control principle, a priority should be provided to Route-3 bus, but not to Route-1 and Route-2 buses. However, a priority to Route-3 bus will inevitably “force” 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.

Also note that a priority provided to the major road will certainly increase the delay of vehicles on the crossing street. Thus, how to properly make a priority decision based on the overall system benefits becomes an important issue for TSP operations. The model presented hereafter is developed to address this issue.

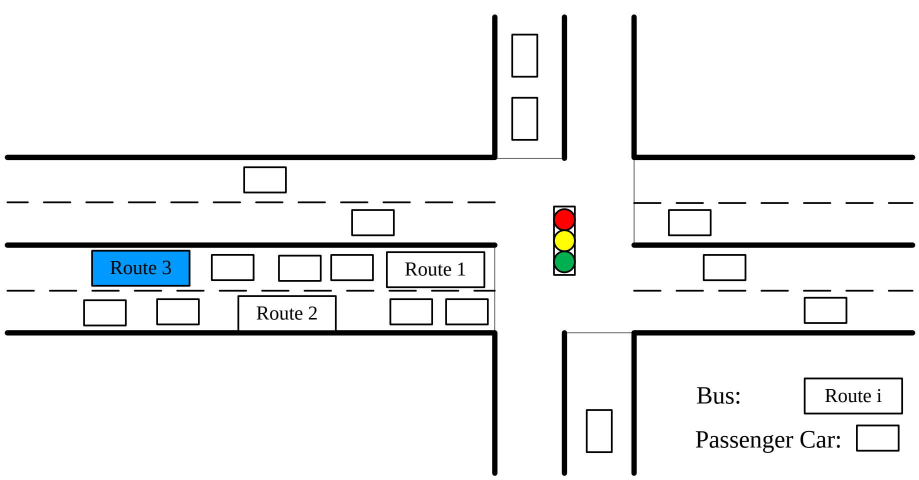

FIGURE 2 Impacts of bus sequences over different routes at the intersection

MODEL DEVELOPMENT

The proposed control system aims to reduce the bus headway variance with the TSP control so as to minimize the total passenger waiting time at their next bus stops. Most conventional TSP controls provide a fixed time (i.e., 15 s) for green extension or red truncation when giving a priority to buses. Recent technology advance, however, has enabled a TSP to provide variable priority times, which offer the promise to contend with the multiple-route priority control scenario.

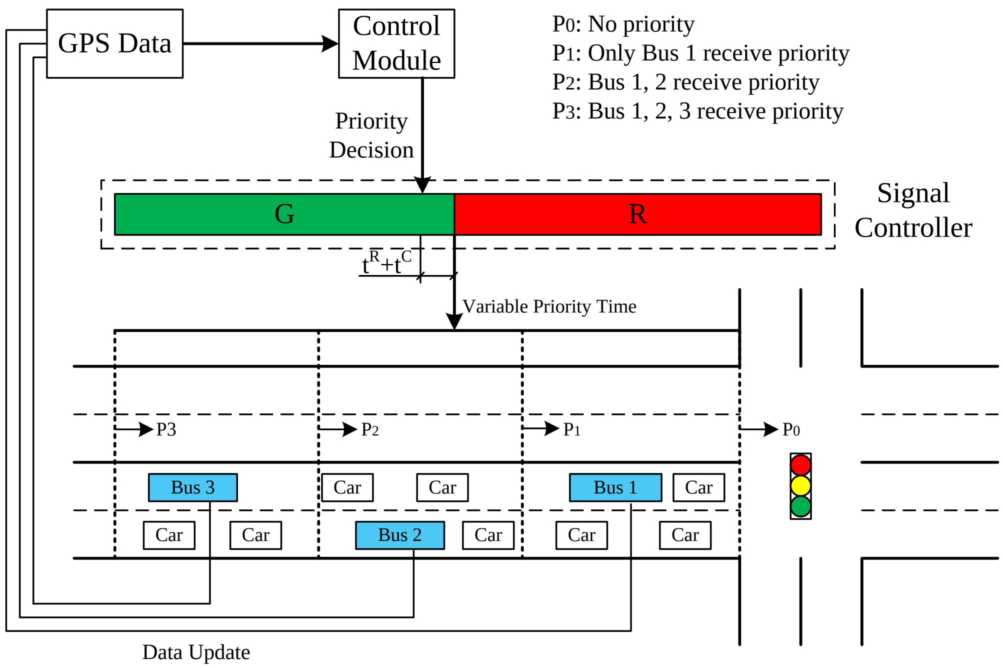

FIGURE 3 Signal control logic of the proposed TSP system

FIGURE 3 illustrates the control structure of the proposed system, where the control module will be activated to process a priority decision at the end of a green phase based on 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 control center, and t^C is the reaction time of signal controllers. Then, the decision outcome will be the number of buses to grant the priority and the required duration for green extension or red truncation.

Note that the control module is designed to make the priority decision based on the available data, where the locations of all buses are assumed to be available via GPS or Automatic Vehicle Location (AVL) systems, and signal controller is able to provide variable priority time. The entire decision-making process for TSP 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 on those non-priority traffic volumes, the maximum allowed priority time is determined by the current v/c ratio on the crossing street:

$$\frac{(v/c)\cdot t_{p,q}^{g}}{(t_{p,q}^{g}-t_{p,q}^{gr})}\leq \beta \tag{2}$$

where, $t_{p,q}^{g}$ is the green duration of non-priority phase p in cycle q without the priority; $t_{p,q}^{gr}$ is the green reduction in the non-priority intersection approach due to the priority extension; and β is the maximum allowed (v/c) ratio on the crossing street after priority. Moreover, the minimum green time is set as follows to ensure the pedestrian safety needs:

$$t_{p,q}^{g}-t_{p,q}^{gr}>t^{\min} \quad \forall p,q \tag{3}$$

where, $t^{\min}$ is the minimal green duration of non-priority phase.

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*) *prior to the end of a green phase.*

Step 4: *Estimate the potential benefits if granting the 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. Since 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 buses 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 follows:

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

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

where, $h_{r,i}^{f}(k)$ and $h_{r,i}^{b}(k)$ are the actual forward and backward headways of bus i on route r at stop k before receiving signal priority; $t_{r,i,p,q}^{SB}$ is the saving time of the bus receiving a priority at phase p of cycle q; and $f_{r,i,p,q}(k)$ is a set of binary variables representing the priority status. Please note that 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 then be increased (i.e., longer than the target headway); otherwise, the actual headway will remain unchanged based on our assumption. 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 arriving sequence, the priority status of each bus can be expressed as follows:

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

where, $et_{r,i,p,q}$ is required extra green time for bus i to pass the intersection at the end of a green phase; $t^{eg}_{p,q}$ denotes the additional green durations for all detected buses, which needs to be optimized. If the $f_{r,i,p,q}(k)$ is equal to zero, the bus i gets the priority. Furthermore, the $et_{r,i,p,q}$ and $t^{eg}_{p,q}$ are used to distinguish the single-bus priority and multiple-bus priority.

The saving time of each bus receiving a priority status can be computed as follows:

$$t^{SB}_{r,i,p,q}=\begin{cases}t^{r}_{p,q}-et_{r,i,p,q}, & \text{if the priority strategy is green extension}\\ et_{r,i,p,q}, & \text{if the priority strategy is red truncation}\end{cases} \tag{7}$$

where, $t^{r}_{p,q}$ is the red time of phase p. Note that the saving time by a green extension is generally much larger than with a red truncation when the bus volume exceeds 60 veh/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 (1):

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

where, $\alpha_{r,i}(k)$ is the average waiting time of passengers for each route; θ_r is the threshold to determine if bus bunch for each route exits; and N is a positive constant for the resulting penalty. And then the total passenger waiting time for different routes at the next stop can be expressed as follows:

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

where, $R_{p,q}$ is the set of the detected bus route; $I_{r,p,q}$ is the set of the detected bus vehicles; β_r is the weighted factor of each route; and $c_{r,i,k}$ represents the number of passengers from bus i when the 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 arriving 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 as follows:

$$t_{r,i,p,q}^{SPC} = \begin{cases} t_{p,q}^{r} - t_{p,q}^{eg} / 2, & \text{if the priority strategy is green extension} \\ t_{p,q}^{eg} / 2, & \text{if the priority strategy is red truncation} \end{cases} \tag{10}$$

Thus, the total person delay reduction for passenger cars when receiving priority with transit vehicles can be shown as follows:

$$d_R^{PC} = TV^{PC} n^{PC} t_{r,i,p,q}^{SPC} q_{p,q}^{PC} \tag{11}$$

where, TV^{PC} is time value of passenger car drivers; and n^{PC} is average number of persons per passenger car. Note that $q_{p,q}^{PC}$ in Equation (11) stands for the estimated queue of passenger cars, and can be estimated with the model proposed by Chang et al. *(13)*.

By the same token, one can calculate the person-delay reduction of bus passengers, when granted a signal, with the following equation:

$$d_R^B = \sum_{r \in R_{p,q}} TV^B n_{r,i}^B(k) t_{r,i,r,q}^{SB} f_{r,i,p,q}(k) \tag{12}$$

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

Step 4.4: *Estimate the increased delay for passenger-car riders on the crossing street.*

Note that granting a priority to buses in the arterial will inevitably reduce the green time on the crossing street, which will consequently cause extra delay for those 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 due to the reduction of green time; and 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:

$$t_{r,i,p,q}^{WPC2} = \begin{cases} t_{p,q}^{eg}, & \text{if the priority strategy is green extension} \\ t_{p,q}^{r} + t_{p,q}^{eg}, & \text{if the priority strategy is red truncation} \end{cases} \tag{13a}$$

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 as follows:

$$t_{r,i,p,q}^{WPC1} = \begin{cases} t_{p,q}^{eg} / 2, & \text{if the priority strategy is green extension} \\ t_{p,q}^{r} + t_{p,q}^{eg}, & \text{if the priority strategy is red truncation} \end{cases} \tag{13b}$$

Hence, one can approximate the increased person delay for passenger cars on the crossing street as follows:

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

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

Based on Equations (9), (11), (12), and (14), one can calculate the total person delay reduction for those on-board bus riders, those waiting at the downstream bus stops, and those passenger vehicles 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 follows:

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

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

Step 5: *Determine the priority strategies and the optimized green duration for the priority requests.*

This system will grant a bus priority to major road with the 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 ;
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 either the extended green duration for the priority phase and the green time reduction for the non-priority approach.

CASE STUDY

Experimental Design

To illustrate the applicability and efficiency of the proposed system, this study has employed VISSIM as an unbiased tool for performance evaluation. Using the VISSIM-COM interface, this study developed a program to simulate bus operations and signal control logic by VB.NET and 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 arriving sequence. FIGURE 4 shows the flow chart of the entire simulator and decision process for the proposed TSP operations. Note that to efficiently search the optimal feasible solution, each candidate solution organized in the ascending order would be tested sequentially.

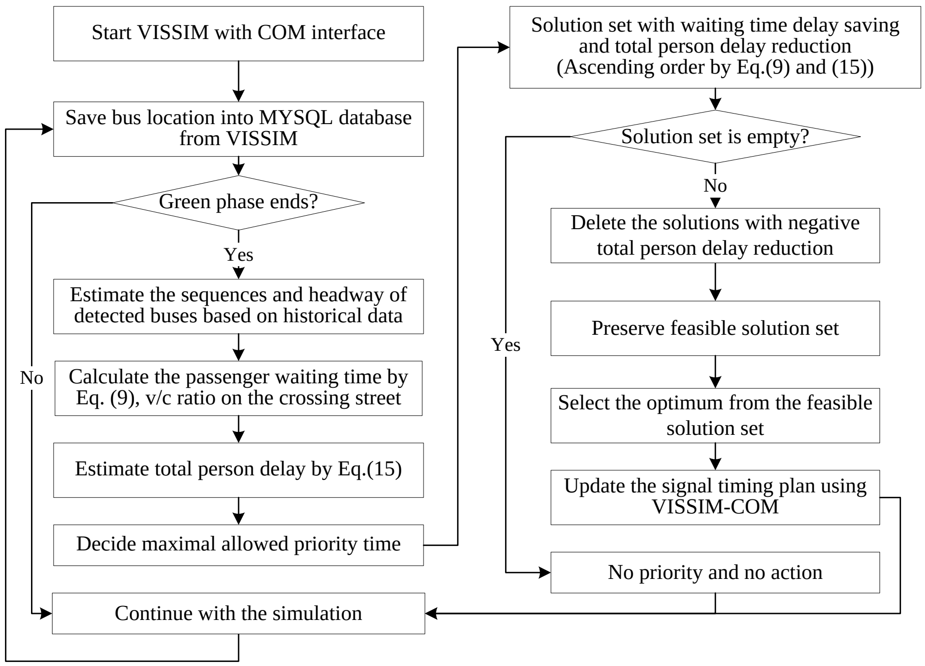

FIGURE 4 Flow chart of simulation evaluation

To evaluate the effectiveness of the proposed decision process for bus signal priority, this study has selected the WeiEr Road in Jinan as a test case. As shown in FIGURE 5, the target arterial is about 4.5 kilometers, and its key traffic and geometry are listed below:

- The total travel distance of bus routes is about 6.0-6.8km;
- The length of the arterial (WeiEr road) is about 3km with two-way 6 lanes;
- The volume and capacity ratio (v/c) is about 0.7;
- The mean headway is about 4 min, the variance observed on the target arterial ranges from 2 to 6 minutes;
- There are 8 bus routes in two directions;
- No bus exclusive lane is available on the arterial;
- There are 6 intersections along the arterial, and only 2 have the function to offer the bus priority function;
- The duration of simulation time is about 3600 seconds;
- The equivalent passenger number for bus and passenger cars is $n_{r,i}^{B}(k) = 20$ and $n^{PC} = 2$ per vehicle, respectively;
- The threshold of bus bunch for each route is $\theta_r = 1.5$ minutes;
- 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 bunch is $N = 10$ minutes; and
- The sum of communication time and reaction time is $t^{C} + t^{R} = 3$ seconds.

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

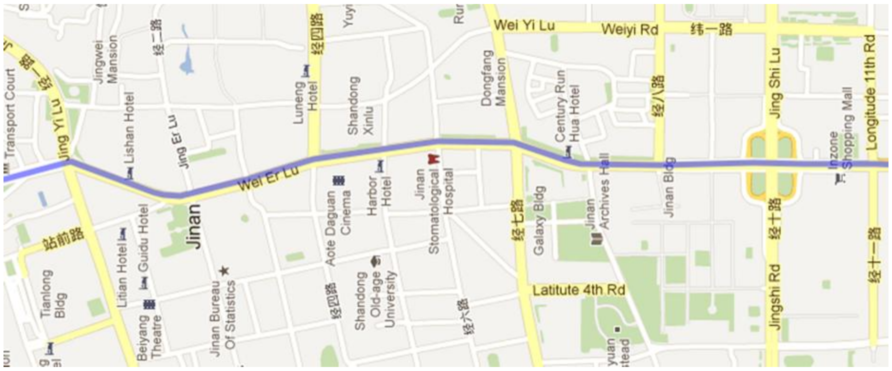

FIGURE 5 A view of WeiEr Road in Jinan, China

Experimental Results

For control efficiency and convenience of case illustration, this study only considers the TSP of green extension in the experimental analysis, and evaluates the proposed strategy with the following three scenarios:

- Scenario 1: no priority control;
- Scenario 2: priority to all requested buses (15s for green extension); and
- Scenario 3: the proposed control with variable green extension.

Several MOEs are 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 compared the results among different scenarios. Some key findings are summarized below:

1). The proposed control in this study can outperform other two methods (See FIGURE 6) 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%).

2). Despite the indifference in average headways among these three controls, the variance of headways with the proposed strategy is far less than that under the other two methods, as shown in FIGURE 6(A). The reductions in variance for routes-2, 12 and 11 are up to 21.7 percent, 31.8 percent, and 44.9 percent, respectively, which are consistent with the reduction in the total passenger waiting time in FIGURE 6(B). Furthermore, the probability of having bus bunch under the control of granting the priority to all buses is 25 percent more than with the proposed strategy.

3). The proposed control method concurrently considers the impacts of signal priority on bus and passenger cars. Therefore, the proposed TSP strategy can also achieve a better performance with response to reduction in bus passenger delay, as shown in FIGURE 6 (C). Note that the bus passenger delay is the sum of increased passenger waiting time and travel time. Compared to the approach of "priority to all buses", the proposed model can significantly reduce the average waiting time. The reason is that some on-time or ahead of time buses are enforced to obtain priority in the "priority to all buses" cases, which will inevitably increase 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 is able to produce less total person delay for the entire arterial during the operational period, since the TSP with the strategy of "priority to all buses" may bring significant impacts on cross-street traffic flows which can lead to a significant increase in the total vehicle delay.

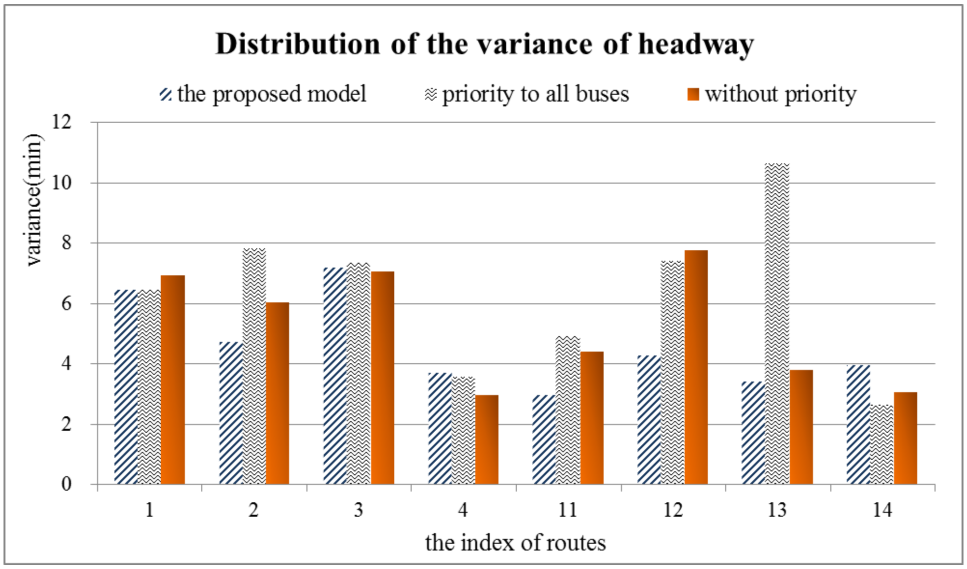

FIGURE 6(A) Distribution of headway variance

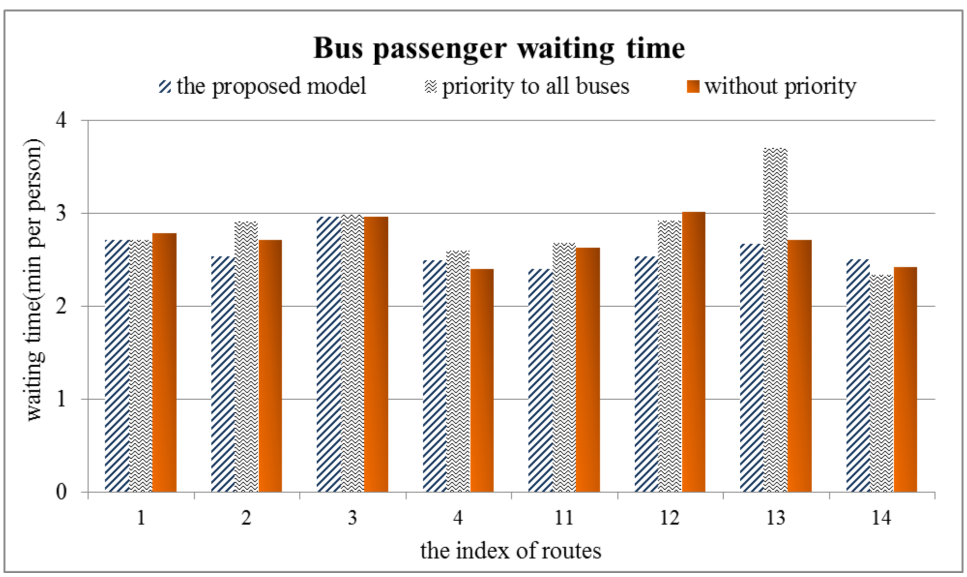

FIGURE 6(B) Bus passenger waiting time

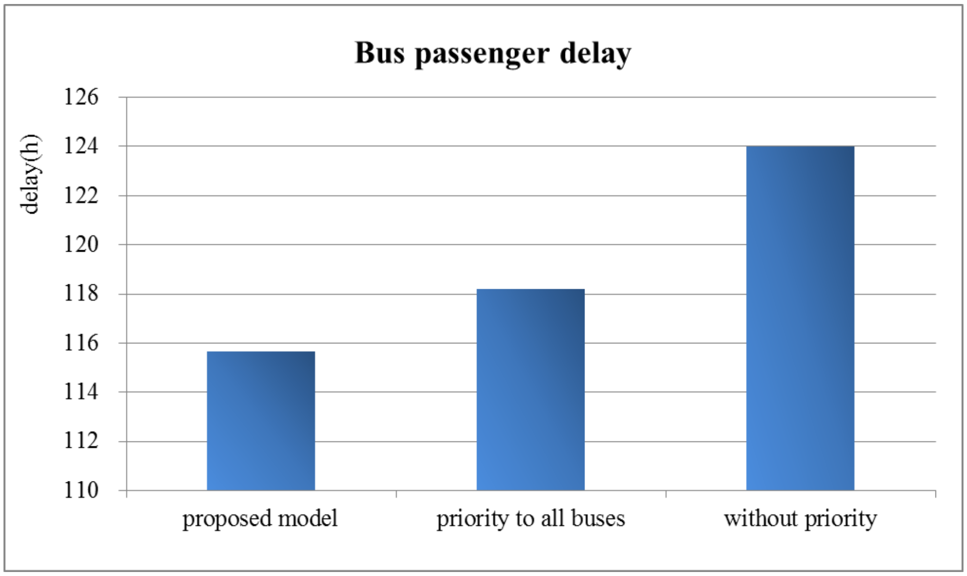

FIGURE 6(C) Total bus passenger delay

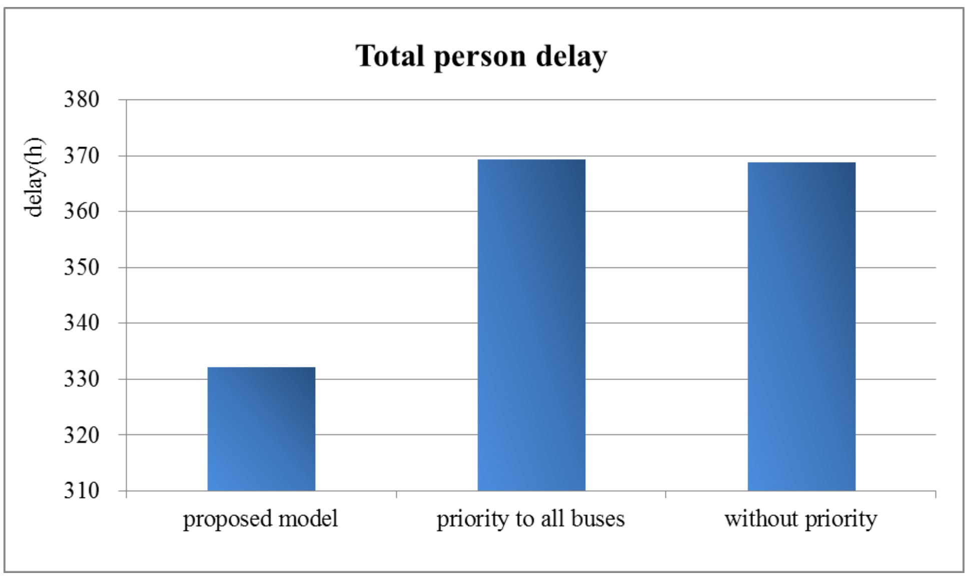

FIGURE 6(D) Total person delay of the entire arterial

FIGURE 6 Comparisons of the three TSP methods

Sensitivity analysis

To evaluate the reliability and effectiveness of the proposed strategy, this study has tested the proposed model's sensitivity 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 crossing street.

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

TABLE 1 The Detailed Description of Different Scenarios

Scenario	Traffic volume at the priority approach (veh/h)	Bus ratio	Traffic volume on the crossing street	The number of bus routes in two directions
A1	1400	1%	420	6
A2	2400	1%	720	6
A3	1400	2%	420	10
A4	2400	2%	720	10
A5	1400	3%	420	16
A6	2400	3%	720	16
A7	1400	4%	420	16
A8	2400	4%	720	16

As shown in FIGURE 7, regardless of the ratio between bus and the traffic volumes, the proposed TSP strategy can always reduce the bus passenger delay (the sum of the waiting time and travel time delay). However, the proposed control strategy will yield much significant reduction in the total network person delay if the ratio between bus and total traffic volumes exceeds 2 percent, and such benefits will increase with the total intersection traffic volume.

Furthermore, 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 at the primary arterial and high percentage of buses.

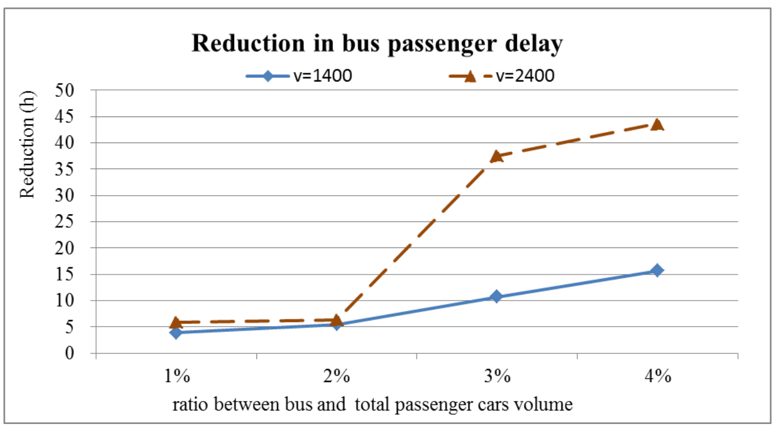

FIGURE 7(A) Reduction in bus passenger delay

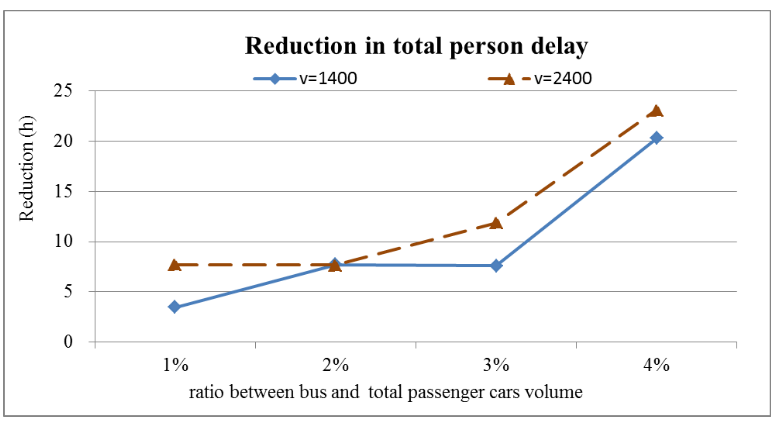

FIGURE 7(B) Reduction in total person delay

FIGURE 7 Comparisons of performance with and without priority

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 crossing street. Due to the overlaps of multiple bus routes, the conventional FCFS strategy often fails to offer an efficiency control, since not every bus in the target link is behind schedule. The proposed model utilizes the variable priority time technique, which is capable to perform a more precise control so as to 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.

Using the field data from Jinan, the performance evaluation 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 has also 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 percent. Such benefits are generally expected to increase with total intersection volume.

Future research along this line will address the following three issues: 1) how to grant the signal priority so as to reduce the impacts on the downstream intersection, because the priority to late bus will also release more passenger cars, which may leads to a congestion at the downstream intersection, especially on those coordinated arterials; 2) conduct more extensive experiments or field tests to validate the reliability and effectiveness of the TSP system under various geometry configurations and traffic demand patterns; and 3) use the bus dwelling time at stops and GPS bus location data to design a bus progression control system on urban arterials.

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