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Research Article

Optimization Model of Transit Signal Priority Control for Intersection and Downstream Bus Stop

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Transit signal priority has a positive effect on improving traffic condition and level of transit service in the urban area. In this paper, a passenger-based transit signal priority (TSP) optimization model is formulated to optimize intersection signal phasing based on minimizing accessibility-based passenger delay at the intersection and increased waiting-delay at the downstream bus stop simultaneously. Genetic Algorithm is utilized to calculate passenger-based optimization model that is calibrated by evening rush hour actual traffic data (17:30–18:30, October 13th–October 15th, 2015) along Shuiximen Boulevard in Nanjing, China. The performance of the proposed optimization model in decreasing delay and improving system reliability is simulated and evaluated by VISSIM-based simulation platform, and the results illustrate that the proposed optimization model presents promising outcomes in decreasing accessibility-based passenger delay at intersection (average reduction of 12%) and passenger waiting-delay at downstream bus service stop (average reduction of 18%) compared with traditional vehicle-based TSP optimization method in rush hour.

1. Introduction

Traffic congestion has been one of the most depressing and challenging problems of urban areas in China, and poor traffic condition will deteriorate the level of safety [1, 2] and pollution [3]. High occupancy vehicle (such as transit vehicle) priority is recognized as one of the most effective strategies for improving traffic condition and level of service by a growing number of transportation professionals. Interaction analysis and cooperation control optimization of transit signal priority is paid more and more attentions on improving passengers' traveling efficiency and decreasing traveling delay, and transit signal priority optimization has become a key issue in the urban traffic control system.

In the area of transit signal priority optimization, Smith and Associates et al. were among the first to conduct bus preemption experiments to reduce bus travel time [4]. Head et al. presented the core logic of a traffic signal controller which can present an analytical framework for the analysis of complex controller behaviors and is demonstrated for the case of multiple priority requests [5]. Since then, many studies have proposed TSP scenarios and reported benefits of various practices.

The intersection is the basic optimized unit for transit signal priority control, and isolated intersection within arterial and networks are focused on for transit signal priority optimization, respectively. Dion and Hellinga described the structure of the Signal Priority Procedure for Optimization in Real-Time (SPPORT) model and demonstrated its capabilities on an isolated intersection for a range of traffic demands and with and without transit vehicles [6]. Christofa and Skabardonis presented a real-time, traffic-responsive signal control system for signal priority on conflicting transit routes that also minimized the negative effects on auto traffic, and the system was tested through simulation at a complex signalized intersection located in Greece [7]. Dion et al. focused on an arterial corridor in Virginia for evaluating types of TSP in a fixed, coordinates system using simulation-based method [8]. Vasudevan designed a real-time robust arterial signal control system that can give priority to buses while simultaneously maximizing progression bandwidths and optimizing signal timing plans at each intersection along the arterial [9].

Ma et al. presented a coordinated transit priority control optimization model that can provide effective priority control for transit while minimizing adverse impacts on general traffic movements along the coordinated intersection group between two successive bus stops [10]. Mesbah et al. presented a detailed formulation to optimize transit road space priority at the network level and utilized an efficient heuristic method to find the optimum solution [11]. Besides intersection, the bus stop is another key point for TSP optimization. Ngan examined the impact of nearside bus stop on transit signal priority implementation using the microsimulation model VISSIM [12]. Kim and Rilett proposed an improved transit signal priority algorithm for networks which attempt to reduce the negative effects of nearside bus stops on TSP operations [13]. Feng analyzed the joint impact of different kinds of factors and improvement strategies on bus traveling reliability at the stop-to-stop segment level using the data along an urban arterial corridor in Portland, Oregon [14].

Depending on the TSP focus, operating agencies may select different control objectives to improve their service reliability. Ma et al. presented a control objective of minimizing the total delay for all detected transit vehicles [15]. Christofa and Skabardonis extended the objectives to reduce the total vehicle delay of auto and transit [7]. Chang et al. chose the total passenger delay of general and transit as the control objective [16]. Christofa et al. presented a person-based transit signal priority optimization system on conflicting transit routes [17]. Furth and Muller developed a method of transit signal priority control which takes transit schedule adherence as the control target [18]. Hounsell and Shrestha proposed a method for cooperative bus signal priority strategy regarding optimizing headway of itself and the following buses [19].

Most previous studies focused merely on transit signal priority optimization considering intersections and bus stop downstream simultaneously while intersection and nearside bus stop (especially downstream bus service stop) interaction will seriously affect the performance of TSP for improving traffic efficiency. Moreover, optimization algorithms and evaluation methods of intersection TSP control regarding system delay and reliability comprehensively need further development.

The research in this paper proposes an improved transit signal priority optimization model for signal control unit (intersection and downstream bus stop segment, shown in Figure 1), and analysis and evaluation are presented using VISSIM-based simulation platform; this research includes the following main features:

(1) Accessibility-based passenger delay at an intersection and increased waiting-delay at the downstream transit schedule control spot (mainly referring to a bus stop) are minimized simultaneously for optimizing signal phasing of signalized intersection.

(2) An illustration of the effectiveness of the passenger-based TSP optimization model compared with traditional vehicle-based TSP optimization method is simulated by VISSIM-based simulation platform.

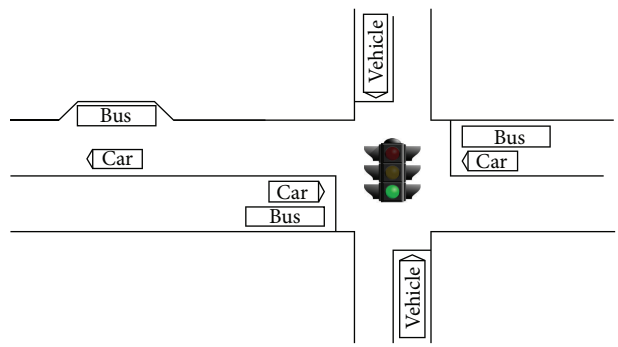

Figure 1: Layout of signal control unit.

This paper is organized as follows. In Section 2, the research methodology flowchart is proposed. In Section 3, passenger-based transit signal priority optimization model that can minimize accessibility-based passenger delay at an intersection and increased waiting-delay at bus stop simultaneously is formulated for generating signal phasing at the intersection. Section 4 is the analysis and evaluation of the proposed optimization model calibrated by actual data in Nanjing, China, and Genetic Algorithm solves the optimization model. Then, the performance of proposed optimized model in decreasing passenger waiting-delay at intersection and bus service stop is evaluated in comparison with traditional vehicle-based TSP optimization model using VISSIM-based simulation platform. In the end, conclusions and recommendations are included.

2. Research Framework

Figure 2 illustrates the flowchart of this research, and the process is divided into model establishment phase, solution phase, and evaluation phase. Passenger-based TSP optimization model is formulated for minimizing accessibility-based passenger delay at an intersection and increased passenger waiting-delay at the downstream bus stop in the first phase. For the second phase, the proposed optimization model that is calibrated using actual data of Nanjing (in China) is calculated by the Genetic Algorithm. At last phase, VISSIM-based simulation platform is built for analyzing and evaluating the performance of passenger-based TSP optimization model in decreasing passenger delay at an intersection and downstream bus stop.

3. Methodology

A passenger-based transit signal priority optimization model is formulated to optimize intersection signal phasing for minimizing accessibility-based passenger delay at intersection and increased waiting-delay at bus stop.

3.1. Notations. All definitions and notations used in the model formulation are summarized in the following:

d_{Ip}: Accessibility-based passenger delay at intersection (s)

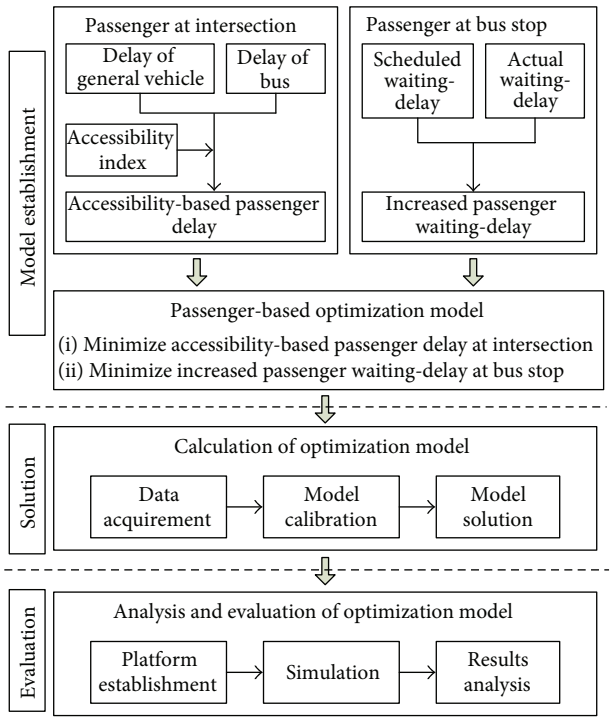

Figure 2: Methodology flowchart.

ΔD: Increased passenger waiting-delay at bus stop (s)

d_{cp}: Passenger delay of general vehicle at intersection (s)

$\overline{d}_{cij}$: Average delay of general vehicle for phase j of cycle i at intersection (s)

q_{cij}: Arrival rate of general vehicle for phase j of cycle i at intersection

P_{cij}: Average passenger occupancy of general vehicle for phase j of cycle i at intersection (per)

λ_{cij}: Green time ratio of general vehicle for phase j of cycle i at intersection

x_{cij}: Degree of saturation of general vehicle for phase j of cycle i at intersection

d_{bp}: Passenger delay of transit vehicle at intersection (s)

$\overline{d}_{bi}$: Average delay of transit vehicle in cycle i at intersection (s)

q_{bi}: Arrival rate of transit vehicle in cycle i at intersection

P_{bi}: Average passenger occupancy of transit vehicle in cycle i at intersection (per)

λ_{bi}: Green time ratio of transit vehicle in cycle i at intersection

x_{bi}: Degree of saturation of transit vehicle in cycle i at intersection

f_a: Accessibility index

ρ: Density of transit network

$\overline{X}$: Transfer coefficient

γ_R: Coverage rate of bus stop

D: Actual passenger waiting-delay at bus stop (s)

t_f^m: Actual headway between transit $\#m-1$ and transit $\#m$ (s)

r_a^m: Actual arrival rate of passenger for transit $\#m$ at bus stop

t_s^m: Actual dwell time of transit $\#m$ at bus stop

r_b^m: Actual boarding rate of passenger for transit $\#m$ at bus stop

$\widehat{D}$: Scheduled passenger waiting-delay at bus stop (s)

$\widehat{t}_f^m$: Scheduled headway between transit $\#m-1$ and transit $\#m$ (s)

$\widehat{r}_a^m$: Scheduled arrival rate of passenger for transit $\#m$ at bus stop

$\widehat{t}_s^m$: Scheduled dwell time of transit $\#m$ at bus stop

$\widehat{r}_b^m$: Scheduled boarding rate of passenger for transit $\#m$ at bus stop.

3.2. Passenger-Based Optimization Model. Considering the variability of occupancy for auto and transit, total passenger delay at an intersection will be more suitable for transit operation optimization. Also, schedule adherence can reflect the reliability of transit system operation, and the deviation of actual arrival time from schedule will increase passenger waiting-delay at transit schedule control spot (mainly referring to the bus stop). In this paper, passenger delay at the intersection and increased passenger waiting-delay at bus stop owing to deviation from the schedule are paid attention simultaneously for transit signal priority control optimization, and the passenger-based TSP optimization model that minimizes these two indexes is formulated in

$$\begin{gathered}\min d_{Ip} \\ \min \Delta D.\end{gathered} \tag{1}$$

3.3. Accessibility-Based Passenger Delay at Intersection. Considering the different movement characteristic of the general vehicle and transit vehicle at an intersection, passenger delay model of auto and transit should be proposed, respectively.

Regarding Webster's delay formula, total passenger delay of auto and transit at one intersection is addressed in

$$
\begin{aligned}
d_{cp} &= \sum_{i-1}^{T/C} \sum_{j=1}^{j} \left(\overline{d}_{cij} \times q_{cij} \times P_{cij}\right), \\
\overline{d}_{cij} &= \frac{C\left(1-\lambda_{cij}\right)^2}{2\left(1-\lambda_{cij}x_{cij}\right)} + \frac{{x_{cij}}^2}{2q_{cij}\left(1-x_{cij}\right)} \\
&\quad - 0.65\left(\frac{C}{{q_{cij}}^2}\right)^{1/3} {x_{cij}}^{(2+5x_{cij})}, \\
d_{bp} &= \sum_{i-1}^{T/C} \left(\overline{d}_{bi} \times q_{bi} \times P_{bi}\right), \\
\overline{d}_{bi} &= \frac{C\left(1-\lambda_{bi}\right)^2}{2\left(1-\lambda_{bi}x_{bi}\right)} + \frac{{x_{bi}}^2}{2q_{bi}\left(1-x_{bi}\right)} \\
&\quad - 0.65\left(\frac{C}{{q_{bi}}^2}\right)^{1/3} {x_{bi}}^{(2+5x_{bi})}.
\end{aligned}
\tag{2}
$$

Compared with general vehicle, the traveling accessibility of transit is low. The degree of attraction to passengers for traveling mode choice will be significantly influenced by traveling accessibility. Hence, the level of influence under the effect of traveling accessibility should be focused on. As we know, the density of transit network, transfer coefficient, and coverage rate of bus stop remarkably reflect the accessibility of transit network, and accessibility index model of transit can be calculated as below:

$$f_a = f\left(\rho, \overline{X}, \gamma_R\right). \tag{3}$$

Then, accessibility-based passenger delay at an intersection is shown in

$$d_{Ip} = f_a d_{bp} + d_{cp}. \tag{4}$$

3.4. Increased Passenger Waiting-Delay at Bus Stop. The scheduled and actual processes of passengers' arrival and waiting at bus stop bay for boarding transit vehicle are illustrated in Figures 3 and 4.

Shadow area surrounded by $\widehat{r}_a^m$, $\widehat{r}_b^m$ and time axis is passenger scheduled delay for bus #m at bus stop bay, and shadow area surrounded by r_a^m, r_b^m and time axis is actual passenger delay for bus #m at bus stop bay. Increased passenger waiting-delay model at bus service stop during time T is established (illustrated in (5)) using delay graphical method:

$$
\begin{aligned}
\Delta D &= D - \widehat{D}, \\
D &= \sum_{m=1}^{m} \left(\int_0^{t_f^m} \left(t_f^m - t\right) r_a^m dt - \int_0^{t_s^m} \left(t_s^m - t\right) r_b^m dt \right), \\
\widehat{D} &= \sum_{m=1}^{m} \left(\int_0^{\widehat{t}_f^m} \left(\widehat{t}_f^m - t\right) \widehat{r}_a^m dt - \int_0^{\widehat{t}_s^m} \left(\widehat{t}_s^m - t\right) \widehat{r}_b^m dt \right).
\end{aligned}
\tag{5}
$$

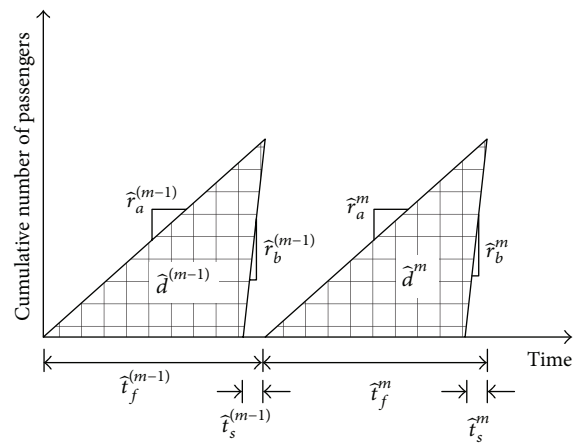

Figure 3: Passengers' scheduled waiting-delay at bus stop.

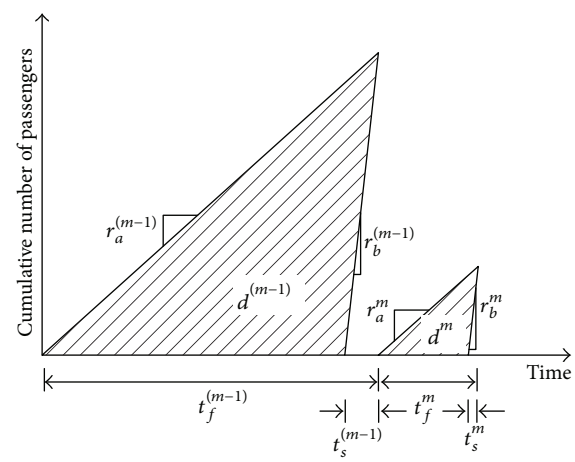

Figure 4: Passengers' actual waiting-delay at bus stop.

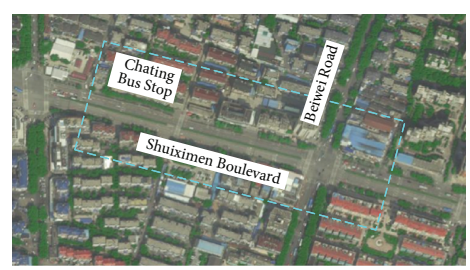

Figure 5: Layout of experimental control unit.

4. Case Study

Shuiximen Boulevard is a major commuter arterial located in the West residential area of Nanjing, China. The experimental control unit (the area that is surrounded by the dotted line in Figure 5) in this paper including a signal intersection (intersection of Shuiximen Boulevard and Beiwei Road) and a bus service stop (Chating Bus Stop) downstream. Transit routes #7, #37, #41, #48, #109, #161, #166, and #204 operate along Shuiximen Boulevard and stop at Chating bus service stop in the peak travel direction (east-west), and the average

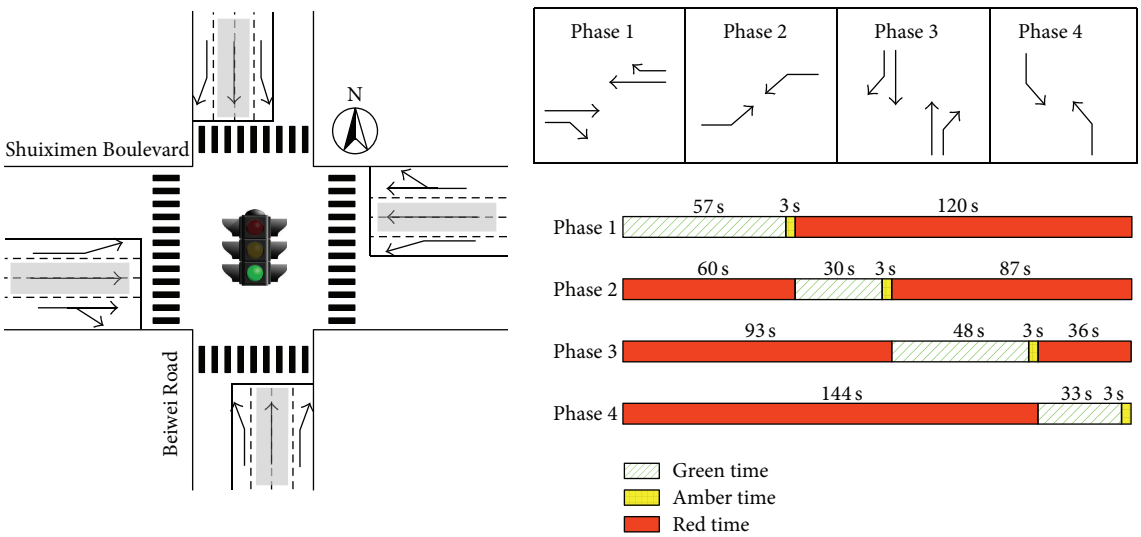

Figure 6: Layout and signal phasing for the intersection of Shuiximen Boulevard and Beiwei Road.

headway of these bus routes range from 6 min to 10 min during the evening rush hour.

4.1. Geometric Conditions and Traffic Patterns. The geometric conditions and original signal phase plan (without TSP strategy) for the intersection of Shuiximen Boulevard and Beiwei Road are shown in Figure 6. The eastbound and westbound approaches have two through lanes, one exclusive left-turn lane and one through/right-turn shared lane. The northbound and southbound approaches have two through lanes, one exclusive left-turn lane and one exclusive right-turn lane. The cycle of this intersection signal phase is 180 seconds. Phase #1 is provided for the eastbound and westbound through and right-turn movements. Phase #2 is the left-turn phase for eastbound and westbound approaches. Phase #3 is the through and right-turn phases for Beiwei Road. Phase #4 is provided for the northbound and southbound left-turn movements.

Traffic volumes (shown in Table 1) of this intersection in evening rush hour (17:30–18:30) for a third straight day (Oct 13th–15th, 2015) are acquired by Video Identification Technology. Besides transit routes #7, #37, #41, #48, #109, #161, #166, and #204 operate along Shuiximen Boulevard, transit routes #19, #20, #63, #68, #78, #113, #134, #160, #307, and #550 travel through this intersection on other approaches.

Passenger occupancy (PO) during evening rush hour at Chating bus service stop is concluded based on automated passenger count (APC) data and the empirical calculation of Nanjing Transit Agency, and the PO of transit routes #7, #37, #41, #48, #109, #161, #166, and #204 during 17:30–18:30, October 13th–October 15th, 2015, is illustrated in Figure 7. Dwell time (DT) and delay deviation of actual arrival time from scheduled time (DAT) of these transit routes at this bus stop are acquired based on bus automatic vehicle location (AVL) data, and these data during evening rush hour (17:30–18:30, October 13th–October 15th, 2015) are shown in Figures 8 and 9.

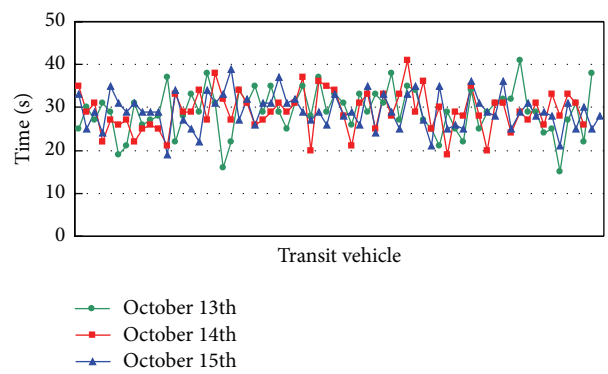

Figure 7: PO of transit vehicle at bus stop in evening rush hour.

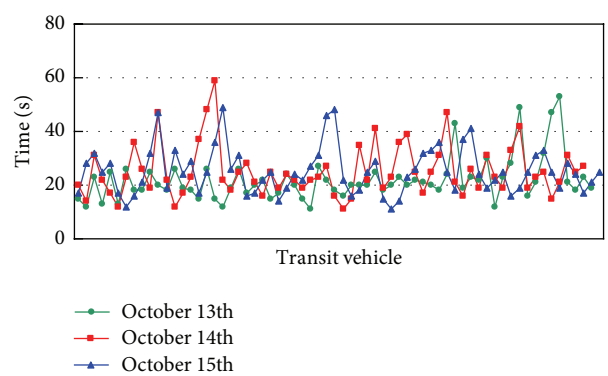

Figure 8: DT of transit vehicle at bus stop in evening rush hour.

Several preliminary experiments were performed to determine if the lane vehicle capacity can be 1700 vehicles per lane per hour approximately [20], and the bus lane capacity can cover nearly 850 buses per lane per hour [21]. Average passengers occupancy of the general vehicle and other transit vehicles at this intersection during rush hour is 1.8 and 25 persons per vehicle, respectively, and these data are acquired

Table 1: Traffic volumes for the intersection of Shuiximen Boulevard and Beiwei Road.

		LT Veh (veh)	TH Veh (veh)	RT Veh (veh)	LT Bus (bus)	TH Bus (bus)	RT Bus (bus)
October 13th	EB	148	714	235	NA	61	8
	WB	161	845	209	20	65	30
	SB	170	654	286	33	14	NA
	NB	206	565	229	7	15	22
October 14th	EB	134	658	216	NA	63	7
	WB	150	811	225	21	66	29
	SB	160	615	288	31	13	NA
	NB	185	554	210	8	15	23
October 15th	EB	154	721	226	NA	65	8
	WB	159	881	200	22	64	32
	SB	161	678	262	31	14	NA
	NB	199	582	241	7	16	21

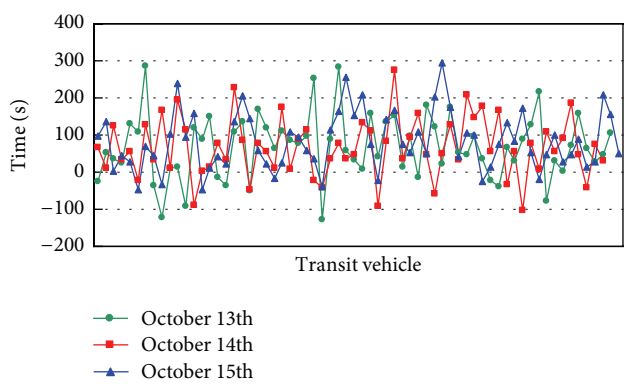

Figure 9: DAT of transit vehicle at bus stop in evening rush hour.

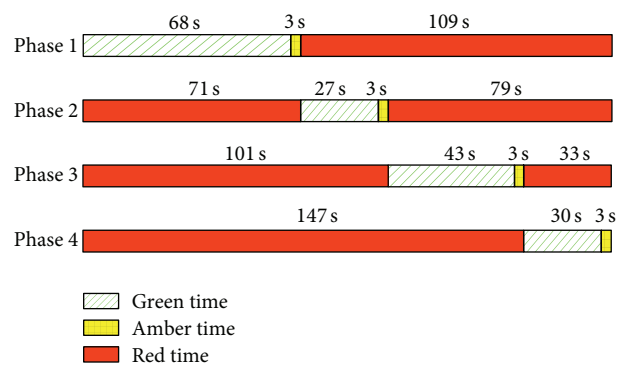

Figure 10: TSP optimization phasing plan at intersection.

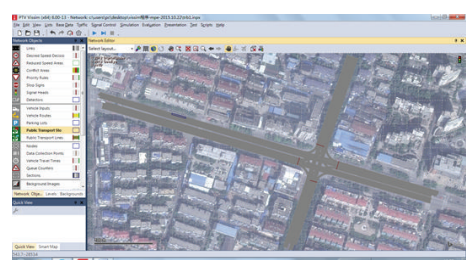

Figure 11: VISSM software simulation platform interface.

by observers that received special training. Accessibility index of the transit vehicle is 0.2.

4.2. Experimental Results and Evaluation

4.2.1. Experimental Results. Two assumptions are put forward before result generation and optimization.

(i) The capacity for each approach at the intersection of Shuiximen Boulevard and Beiwei Road is fixed and not affected by traffic operations.

(ii) The saturation flow degree of vehicles for all approaches at the intersection of Shuiximen Boulevard and Beiwei Road is no more than 90%.

GAs are heuristic, near-optimal solution search methods based on natural genetics and mechanisms of natural selection [22]. In this paper, Genetic Algorithm (GA) toolbox in MATLAB Software is utilized to solve proposed TSP optimization model that is calibrated by the data of experimental control unit along Shuiximen Boulevard, and the value of GA operational parameters is including the following: population is 300 individuals, mutation rate is 0.1%, crossover rate is 70%, chromosome length is 4, and generation number is 50. Proposed optimization model calibrated by traffic data in Nanjing is calculated using Genetic Algorithm, and the optimization phasing plan considering TSP scenarios (green extension) at the intersection of Shuiximen Boulevard and Beiwei Road is illustrated in Figure 10.

4.2.2. Experimental Analysis and Evaluation. Simulation platform (Figure 11) is presented for analyzing and evaluating the performance of signal phasing plans at Shuiximen Boulevard and Beiwei Road intersection with Chating bus stop downstream using VISSIM software, and average delay of auto and transit at this intersection for original signal plan without TSP, traditional vehicle-based TSP plan, and proposed (passenger-based) TSP plan in this paper are presented based on this simulation platform.

Table 2: Simulated delay of control unit for three signal plans.

		October 13th	October 14th	October 15th
Original signal plan without TSP	PDI	1127658	1098562	1199867
	IPDS	86579	84673	87470
Traditional vehicle-based TSP plan	PDI	1067892	1031550	1142273
	IPDS	80345	77222	81872
Passenger-based TSP plan	PDI	988956	948059	1061882
	IPDS	70389	66384	73999

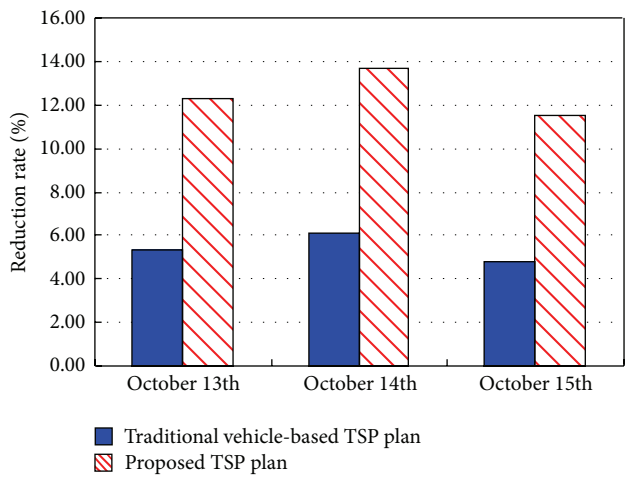

Figure 12: PDI comparisons of optimization methods for delay reduction ratio.

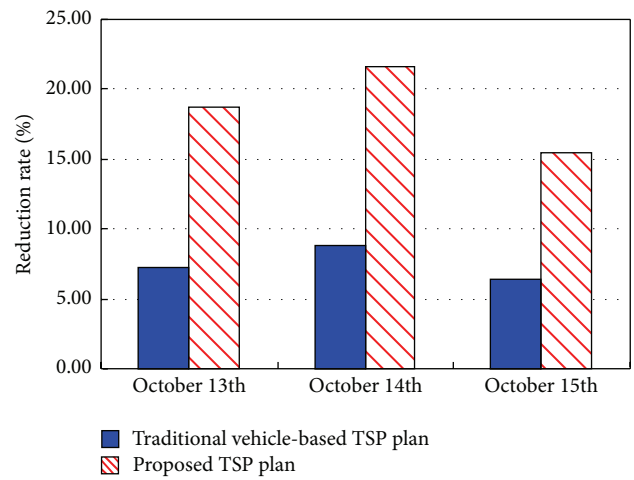

Figure 13: IPDS comparisons of optimization methods for delay reduction ratio.

Total passenger delay at the intersection of Shuiximen Boulevard and Beiwei Road is calculated regarding passenger occupancy of auto and transit, arrival rate, and average delay at the intersection. Total passenger delay at Chating bus stop is generated based on the average delay of buses, transit arrival rate, and passenger boarding rate. Deviation of delay at the bus stop is calculated by comparing with scheduled arrival time and actual arrival time that is acquired from simulation platform. Table 2 summarizes accessibility-based passenger delay at this intersection (PDI) and increased passenger delay at the downstream bus stop (IPDS) during evening rush hour for these three signal plans regarding test data and VISSIM-based simulation platform.

Figures 12 and 13 illustrate the reduction ratio of traditional vehicle-based TSP plan and proposed TSP plan from original signal plan for PDI and IPDS during evening rush hour (17:30–18:30) of a third straight day (Oct 13th–15th, 2015) based on the simulation analysis data shown in Table 2.

The results of Figures 12 and 13 demonstrate significant reductions in passenger delay at this intersection (PDI) and increased passenger delay at the downstream bus stop (IPDS) during evening rush hour at the test intersection for these two TSP optimization plan. The performance of these two TSP optimization methods in decreasing PDI and IPDS on October 15th (traffic volume on October 15th reaches saturation) is not better than other two days in evening rush hour. Therefore, the performance has a strong relationship with traffic volume. Compared with traditional vehicle-based TSP plan, the proposed (passenger-based) TSP plan performs better in delay reduction and improving the reliability of transit system.

5. Conclusion

This paper develops a passenger-based transit signal priority optimization model that can minimize accessibility-based passenger delay at the intersection and increased waiting-delay at bus stop simultaneously. Consequently, optimization phasing plan of intersection is generated using the Genetic Algorithm. At last, case study results validated the effectiveness of the proposed passenger-based model in comparison with traditional vehicle-based TSP optimization method, and the performance of optimization model in decreasing PDI and IPDB is analyzed and evaluated under different traffic demand patterns by use of VISSIM-based simulation platform. Simulation results demonstrate that the proposed passenger-based optimization model can significantly decrease passenger waiting-delay at intersection and bus stop downstream for the control unit (intersection and downstream bus stop).

In the future, urban traffic network optimization model should be focused on further for improving the efficiency and reliability of transit system and minimizing the negative

impacts on the general vehicle under complex traffic condition.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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