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Research Article

An Overlapping Phase Approach to Optimize Bus Signal Priority Control under Two-Way Signal Coordination on Urban Arterials

Zijun Liang[1], **Yun Xiao**[1], **and Yun-Pang Flötteröd**[2]

[1]*School of Urban Construction and Transportation, Hefei University, Hefei 230601, China*
[2]*Institute of Transportation Systems, German Aerospace Center, Berlin, Germany*

Correspondence should be addressed to Zijun Liang; lzj@hfuu.edu.cn

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With the consideration of the uneven traffic volume distribution at intersections on urban arterials, this paper aims to minimize the overall passenger delay (buses and private vehicles) at intersections and identify the applicable conditions of the proposed method with field data. The overlapping phase-based signal control logic and the bus priority control algorithm under two-way signal coordination on arterial roads are proposed. The vehicular capacities and occupancies for buses and passenger cars are considered in the evaluation of the method performance. A field test was carried out at two major intersections on an arterial road in Hefei, China. With the test data, the proposed method is examined and the possible influencing factors are analyzed for identifying the corresponding applicable conditions. The analysis result shows that the application of the overlapping phase helps to provide a relatively flexible signal control for the varying traffic demands at intersections. Compared to the conventional phase, it isof more practical significance to consider overlapping phase and apply bussignal priority control under two-way signal coordination according to the condition of uneven traffic volumedistribution at intersections on urban arterials. The proposed method can effectively decrease the total passenger delay at the intersections on urban arterials under certain applicable conditions. The possible factors influencing the method applicability are identified as well. It is verified that bus signal priority control under the two-way signal coordination, based on overlapping phases, is more conducive to improving traffic efficiency on urban arterials. Regarding the influencing factors and the applicability of the proposed method, the results show that not all situations are conducive to decreasing passenger delay at intersections. The proposed method should be applied under certain applicable conditions and principles in order to efficiently and effectively improve the traffic efficiency on arterial roads.

1. Introduction

Traffic congestion is becoming more common in many cities [1, 2] of China, and vigorous development of the rapid public transportation is an effective way to enhance the attraction of public transportation, which is of great significance to ease traffic burden in urban areas and implement the bus priority strategy at the national level. The adaptive urban traffic signal control system for bus priority was studied for many years. Different approaches have been proposed and helped to decrease buses' waiting time, ensure bus schedule punctuality, and remain regular bus headway. For example, Wang et al. [3] proposed a signal priority control method for bus rapid transit (BRT) according to the optimal comprehensive traffic efficiency. This method can effectively improve BRT's operation efficiency, while the traffic in the nonpriority phases is less affected. Guo and Zhang [4] developed a new transit signal priority control model, based on passenger delay. With this model, the adequate cycle length can also be derived with the objective to minimize the total passenger delay at intersections. The corresponding vehicular delay average and passenger delay per intersection can be reduced to a certain degree accordingly. Although these studies focused on isolated intersections, they are valuable when investigating the influence of bus signal priority control on traffic efficiency and delay in each phase at a given intersection.

However, the abovementioned methods focus rather on the bus signal priority at isolated intersections and cannot further improve the overall operating efficiency of buses along arterial roads. It is because traffic situation at each intersection also influences the traffic operations at its neighbored intersections. Such influence will further spread to the whole network. It is therefore very important to study the control method of bus signal priority under the signal coordination on arterial roads [5]. Generally, there are two strategies for bus signal priority control under the signal coordination on arterial roads, i.e., passive priority control (PPC) and active priority control (APC). Cai and Wang [6] proposed an integrated scheme of bus priority considering variable speed guidance. Based on the given historical data, such as the existing bus demand, bus stop locations, and the surrounding traffic situation, bus delay can be significantly reduced by guiding a bus at a proper and precise speed, with which the number of stops made by the bus is minimized. Yuan [7] applied a MATLAB graphical method to coordinate traffic signals for both buses and private vehicles. The synchronous green wave coordination between buses and private vehicles was realized after conducting the coordination twice. The abovementioned methods belong to the PPC strategy, which are relatively easier to implement in comparison to the methods, based on the APC control strategy. However, the PPC-based approaches focus on the reduction in bus travel time and delay in the coordinated directions and pay less attention to the corresponding impacts on the other driving directions. With the APC strategy, real-time bus signal priority control can be realized by using sensor technologies, like ground detection and vehicle video detection, wireless communication technologies, such as wireless sensor network and vehicular Ad-Hoc network [8, 9]. Xu et al. [10] developed an advanced signal priority technique for a BRT system along an arterial with permitted signal coordination. The adopted objective is to expedite BRT vehicles' operating speed and minimize the negative effect of signal priority on general traffic. The effectiveness of the proposed method was verified with a simulation study. However, there is a drawback in the method, i.e., the algorithm is not suitable when overlapping phases exist. Wang [11] applied the delay control and the compensation mechanism in the implementation of a bus priority strategy under arterial signal and simulated the proposed method with the respective visual agent programming (VAP) model. However, the impact on the traffic in the noncoordinated and nonpriority directions was not analyzed in their study. Gao et al. [12] designated a double-level priority framework to achieve bus signal priority under the signal coordination on arterial roads. In their proposed framework, the strategies green time extension and green time advance were adopted. However, the simulation results showed that the overall vehicular delay on the analysis arterial road was increased. Bie et al. [13] also used green time extension and green time advance to realize the bus priority control on an arterial road and found that multiple-phase bus signal priority strategy can reduce the overall network delay more significantly. In order to decrease the impact on private cars at intersections, both [12, 13] adopted the APC strategies, green time extension and green time advance. The overall vehicle delay at intersections has been considered as well. However, the respective algorithms do not consider the situation with overlapping phases and are based on the conventional signal phases, which are usually suitable to the situation when traffic at intersections distributes evenly. When uneven traffic distribution at intersections exists, the conventional phase scheme will inevitably lead to the waste of green time and the increase in vehicle delay.

Cai et al. [14] proposed a flexible online transition structure of traffic signal phases with use of the overlapping phase. In their study, the overlapping phase is a transitional phase for one-way through and left-turn traffic and is applied to satisfy the control need of the uneven traffic flow distribution at intersections. An overlapping phase is placed between the phases for two-way through and left-turn traffic streams if such phase exists in the signal timing plans. Based on this phase structure, the bus signal priority control strategy at an isolated intersection was further studied in [15]. However, only few studies on the bus signal priority control under two-way signal coordination have considered the phase combination with the overlapping phase.

In the aspect of evaluation, traffic efficiency and vehicle delay are mostly used as key performance indicators. However, because of the obvious difference in vehicle capacity between buses and private cars, the ultimate purpose of bus priority at signalized intersection is to reduce the delay of passenger and optimize the efficiency of the system, and the vehicle delay indicator may not reflect a people-oriented traffic management philosophy [16, 18]. Guo and Zhang [4] applied the passenger delay as the main indicator for fairly reflecting the benefits of bus priority. Furthermore, fewer real-data based analyses have been made with regard to the change of passenger delay in each direction at intersections. Chen and Yan [19] proposed a method to calculate passenger delay at intersections.

In addition, the signal adjustment for bus priority control under the signal coordination along arterial roads is subject to many conditions/constraints. The total vehicle delay at intersections may not decrease in all cases. Therefore, the relevant influencing factors should be analyzed according to real test data. The applicable conditions of the respective method should then be proposed.

This paper focuses on the above discovered issues and develops a bus signal priority control approach under the two-way signal coordination on arterial roads. Furthermore, a real field study is conducted as well in order to examine the performance of the proposed approach and the related applicability in practice. The remainder of the paper is organized as follows. Section 2 presents the bus priority control logic with overlapping phase, the multiphase control algorithm for bus signal priority, and the passenger delay estimation. Section 3 presents the test and results at two major intersections on an arterial road. Applicability analysis of the method proposed in this paper is discussed in Section 4. Finally, Section 5 summarizes the main outcomes of this paper.

2. Methodology

The proposed approach consists of three parts, i.e., the bus priority control logic with the overlapping phase, the multiphase control algorithm for bus signal priority, and the passenger delay estimation. They are explained in detail as follows.

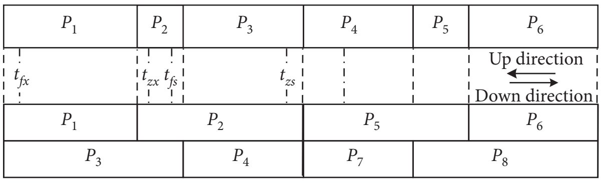


Figure 1: The control logic of the overlapping phase.

2.1. Bus Priority Control Logic with Overlapping Phase. With the consideration of the uneven traffic flow distribution at intersections, the respective signal phases should be relatively flexible. Therefore, the concept of the overlapping phase is applied and embedded in the bus signal priority control logic (see Figure 1). The application of the overlapping phase can help to provide more capacity for the directions with heavy traffic load.

The lower layer in Figure 1 is a double-ring signal phase structure with 8 subphases, indicated as p_1, p_2, p_3, p_4, p_5, p_6, p_7, and p_8. In each subphase, signal coordination and bus priority requests could be located. p_2 and p_3 represent the positive coordinated subphases in one direction and the reverse coordinated subphases in the opposite direction of the road. t_{zx} and t_{zs} are the lower and the upper time threshold of the subphase p_2, while t_{fx} and t_{fs} are the lower and the upper time threshold of the subphase p_3. These time thresholds are the constraints for the two-way signal coordination. Each subphase can be a bus priority subphase, in which the bus priority requests can be accepted. Suppose t_r is the priority request time for a certain bus. Since t_r can be in the different subphases, different priority control logics will be used correspondingly. When the bus priority requests are sent from multiple directions simultaneously, the priority is determined according to the time difference Δs between t_r and the green start time of the bus priority subphase. The smaller the Δs is, the higher priority the respective bus will have.

Moreover, P_1, P_2, P_3, P_4, P_5, and P_6, in the upper layer of Figure 1, are 6 combination phases, i.e., overlapping phases, which are composed of the subphases in the lower layer. The function of the upper layer is to calculate the adjusted green time required for bus priority.

2.2. Multiphase Control Algorithm for Bus Signal Priority. According to the bus priority request time, based on the bus prioritycontrol logic with overlapping phase above, the multiphase control algorithm for bus signal priority can be divided into the coordinated phase algorithm and the uncoordinated phase algorithm. Since these two algorithms are similar in principle, the coordinated phase algorithm is explained in detail here. In order to decrease the impact on private cars at intersections, the APC strategies, green time extension, and green time advance [20, 21] are adopted in this paper. And the coordinated phase algorithm can be divided into the green time extension algorithm and the green time advance algorithm.

2.2.1. Green Time Extension Algorithm. We assume that t_0^n is the time when the bus with the highest priority arrives at the given intersection in the nth cycle, the green start and end time of the positive coordinated subphase are t_{zk}^n and t_{zj}^n, the green start and end time of the reverse coordinated subphase are t_{fk}^n and t_{fj}^n, and the maximum extendable green time of the positive coordinated subphase and the reverse coordinated subphase are t_{zym}^n and t_{fym}^n, respectively. When $t_{zj}^n < t_0^n \le t_{zj}^n + t_{zym}^n$or $t_{fj}^n < t_0^n \le t_{fj}^n + t_{fym}^n$, the green time extension algorithm will be executed. Suppose the extended green times of the positive and the reverse coordinated subphase, required for the implementation of bus priority control, are t_{zy}^n and t_{fy}^n, calculated by equations (1) and (2), t_{zym}^n and t_{fym}^n can be calculated by equations (3) and (4). The signal adjustment diagram is shown in Figure 2.

$$t_{zy}^n = t_0^n - t_{zj}^n, \quad \left(t_{zy}^n \le t_{zym}^n\right), \tag{1}$$

$$t_{fy}^n = t_0^n - t_{fj}^n, \quad \left(t_{fy}^n \le t_{fym}^n\right), \tag{2}$$

$$t_{zym}^n = \sum_{i=4}^{6} t_{giy}^n + t_{g1y}^{n+1}, \quad \left(t_{g1y}^{n+1} = t_{fx}^{n+1} - t_{fk}^{n+1}, t_{giy}^n = t_{gi0}^n - t_{gic}^n\right), \tag{3}$$

$$t_{fym}^n = \sum_{i=3}^{6} t_{giy}^n, \quad \left(t_{giy}^n = t_{gi0}^n - t_{gic}^n\right), \tag{4}$$

where t_{giy}^n, t_{gi0}^n, and t_{gic}^n are the maximum diminished green time, the original green time, and the basic green time of the nonbus priority phase P_i in the nth cycle; t_{g1y}^{n+1} is the maximum diminished green time of phase P_1; and t_{fx}^{n+1} and t_{fk}^{n+1} are the lower time threshold and the start time of the reverse coordinated subphase in the nth + 1 cycle.

The green times of the positive coordinated subphase and the reverse coordinated subphase are t_{gzx}^n and t_{gfx}^n, respectively, and can be calculated by the following equations:

$$t_{gzx}^n = t_{gz0}^n + t_{zy}^n, \quad \left(t_{zy}^n \le t_{zym}^n\right), \tag{5}$$

$$t_{gfx}^n = t_{gf0}^n + t_{fy}^n, \quad \left(t_{fy}^n \le t_{fym}^n\right), \tag{6}$$

where t_{gz0}^n and t_{gf0}^n are the original green time of the positive coordinated subphase and the original green time of the reverse coordinated subphase in the nth cycle, respectively.

Regarding the positive coordinated subphase, the total diminished green time of the other phases can be calculated by the following equation:

$$t_{gi}^n = \max\left(t_{gi\min}, t_{gi0}^n - t_{zy}^n \frac{y_i}{\sum_{i=4}^{6} y_i}\right). \tag{7}$$

With concern to the reverse coordinated subphase, the total diminished green time of the other phases can be calculated by the following equation:

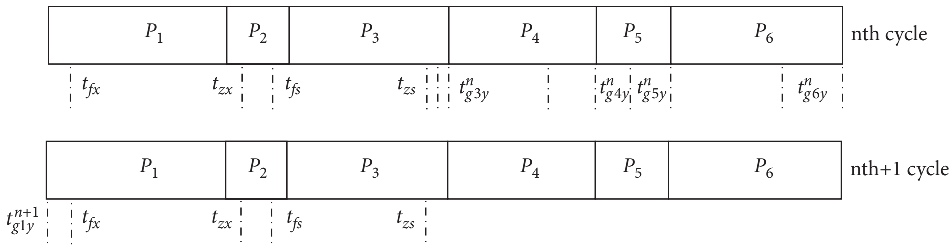


Figure 2: The signal adjustment diagram.

$$t_{gi}^{n} = \max\left(t_{gi\min}, t_{gi0}^{n} - t_{fy}^{n}\frac{y_i}{\sum_{i=3}^{6} y_i}\right), \quad (8)$$

where $t_{gi\min}$ and y_i are the minimum green time and the flow ratio of phase P_i, respectively.

2.2.2. Green Time Advance Algorithm. When $t_0^n > t_{zj}^n + t_{zym}^n$ or $t_0^n > t_{fj}^n + t_{fym}^n$ in the nth cycle, the green time advance algorithm will be undertaken. Suppose the uncoordinated phase P_j is already at the green time stage, when the bus with the highest priority arrives at the intersection in the nth cycle. Then, the green time of P_j and the green times of all phases between P_j and the 1st coordinated phase of the nth +1 cycle need to be diminished, which can be calculated by equations (3) and (4). Considering the constraint conditions of the two-way signal coordination, the total diminished green time of the phases can be calculated by the following equations:

$$\begin{aligned} t_{ztq} &= \min\left(t_{zs}, t_{zj}^{n+1} - t_{zs}^{n+1}, t_{fj}^{n+1} - t_{fs}^{n+1}\right), \\ t_{zs} &= \sum_{i=j}^{6} t_{giy}^{n} + t_{g1y}^{n+1}, \quad j \in \{4,5,6\}, \end{aligned} \quad (9)$$

$$\begin{aligned} t_{ftq} &= \min\left(t_{fs}, t_{zj}^{n+1} - t_{zs}^{n+1}, t_{fj}^{n+1} - t_{fs}^{n+1}\right), \\ t_{fs} &= \sum_{i=j}^{6} t_{giy}^{n}, \quad j \in \{3,4,5,6\}, \end{aligned} \quad (10)$$

where t_{ztq} is the total diminished green time of the other phases in the positive coordinated subphase; t_{ftq} is the total diminished green time of other phases in the reverse coordinated subphase; and t_{zj}^{n+1}, t_{zs}^{n+1}, t_{fj}^{n+1}, and t_{js}^{n+1} have the same meanings as mentioned above but in the nth +1 cycle.

2.3. Passenger Delay Estimation. In order to properly calculate the impact of bus priority on the overall vehicular delay at intersections, the total passenger delay is selected as the evaluation indicator. Based on the revised formula of the average vehicle delay in [16], the average vehicle delay is calculated by the following equation:

$$d_k^{um} = \frac{(C - g^u)^2}{2C\left(1 - y_k^{um}\right)} + \frac{C - g^u}{2Cq_k^{um}} + \frac{q_k^{um}C^2}{2S_k^{um}g^u\left(S_k^{um}g^u - Cq_k^{um}\right)}, \quad (11)$$

where y_k^{um}, q_k^{um}, and S_k^{um} are the flow ratio, the arrival rate, and the saturation flow rate of traffic stream u on lane m, C is the signal cycle length, g^u is the green time, and k is the vehicle type. Vehicle type b and c represent bus and private car correspondingly.

According to [22, 23], the total passenger delay at intersection within a signal cycle can be calculated by the following equation:

$$D_p = P_b \sum_{u=1}^{l}\sum_{m=1}^{n_u} d_b^{um} q_b^{um} C + P_c \sum_{u=1}^{l}\sum_{m=1}^{n_u} d_c^{um} q_c^{um} C, \quad (12)$$

where P_b is the average number of passengers on the bus, P_c is the average occupancy rate per private car, n_u is the number of the lanes in the direction where traffic stream u comes from, and l is the number of the traffic streams.

Suppose the number of the phases at a given intersection is n, P_1 is the bus priority phase, P_v is the nonbus priority phase with the constraint $2 \le v \le n$, the change values of the green time in P_1 and P_v are Δt_1 and Δt_v, the original green times in P_1 and P_v are g_1 and g_v, then the adjusted green time in P_1 is $g_1' = g_1 + \Delta t_1$. The adjusted green time in P_v is then $g_v' = g_v - \Delta t_v\,(\Delta t_v \ge 0)$, where $\Delta t_1 = \sum \Delta t_v$.

When executing the green time extension algorithm, the extended green time in P_1 is Δt_1, and the decreased vehicle delay of the traffic stream on lane m in P_1 can be calculated by the following equation:

$$\Delta d_k^{1m} = \frac{q_k^{1m}\cdot\Delta t_1}{2}\left(2r_1 - \Delta t_1 + \frac{q_k^{1m}\cdot\Delta t_1}{S_k^{1m}}\right), \quad (13)$$

where r_1, q_k^{1m}, and S_k^{1m} are the red time in P_1, the arrival rate on lane m, and the saturation flow of lane m in P_1. Furthermore, the green time of the nonbus priority phase P_v is diminished. The respective red time is therefore extended. Suppose the extended red time in P_v is ΔT_v, the change value of the vehicle delay on lane m in P_v can be calculated by the following equation:

$$\begin{aligned} \Delta d_k^{vm} &= \frac{\Delta T_v q_k^{vm} S_k^{vm}}{2\left(S_k^{vm} - q_k^{vm}\right)}\left(2r_v + \Delta T_v\right) \\ &\quad - \frac{\Delta T_{v+1} q_k^{vm}}{2}\left(2r_v + \frac{\Delta T_{v+1} q_k^{vm}}{S_k^{vm}} - \Delta T_{v+1}\right), \end{aligned} \quad (14)$$

where q_k^{vm} and S_k^{vm} are the arrival rate and the saturation flow rate of lane m in P_v and r_v and ΔT_{v+1} are the red time and the extended green time in P_v.

When performing the green time advance algorithm, the advanced green time in P_1 is Δt_1. The decreased vehicle delay on lane m in P_1 can be calculated by the following equation:

$$\Delta d_k^{jm} = \frac{\Delta t_1 q_k^{1m} S_k^{1m}}{2\left(S_k^{1m} - q_k^{1m}\right)}\left(2r_1 - \Delta t_1\right). \tag{15}$$

Moreover, the change value of the vehicle delay on lane m in P_v can then be calculated by the following equation:

$$\begin{aligned}\Delta d_k^{vm} = {} & \frac{\Delta T_v q_k^{vm}}{2}\left(2r_v + \frac{\Delta T_v q_k^{vm}}{S_k^{vm}} + \Delta T_v\right) \\ & - \frac{\Delta t_{v-1} q_k^{vm} S_k^{vm}}{2\left(S_k^{vm} - q_k^{vm}\right)}\left(2r_v - \Delta t_{v-1}\right),\end{aligned} \tag{16}$$

where Δt_{v-1} is the advanced green time in P_v.

3. Test and Results

3.1. Basic Conditions. Because the models, driving speed and other characteristics of the bus and that of the cars have great differences [24], buses operating mixed with cars can often get stuck in car congestion [25], one strategy for bus priority typically used to minimize negative bus-car interactions is to dedicate an existing car lane for bus-use [26], in order to ensure bus priority, a bus lane is usually set on the approaches of intersections to make sure that the running of buses is not affected by private vehicles [27]. In addition, the basic condition of signal coordination on urban arterial is to select intersections with similar traffic flow and signal cycle for coordinated control. According to this paper, bus signal priority application test need to be carried out under two-way signal coordination on urban arterials. So the test intersections with the conditions of signal coordination and bus exclusive lane are mainly considered to be selected. Therefore, the application tests were carried out at two neighbored intersections along Huizhou Avenue, i.e., Huizhou Avenue-Ziyun Road and Huizhou Avenue-Jinxiu Avenue, in Hefei, China. Huizhou Avenue is the main arterial road, which is in north-south direction. On this avenue, two-way exclusive bus lanes are set in the middle of the road and the video detectors are equipped at the entrances of the abovementioned intersections. Moreover, the Zigbee equipment was used to realize the wireless communication between the buses and the traffic signal controllers. The bus priority equipment was installed on 5 buses of Express Line 1, running on Huizhou Avenue. The general layout of the test area and the equipment location is illustrated in Figure 3. It should be further explained that, due to the limitation of experimental conditions, the equipment provided can only meet the application test of two intersections and five buses, and the collected experimental data basically support the analysis and conclusion of this paper.

Every time when each of the five buses approached the test intersections, a priority request was sent to the corresponding signal controller wirelessly. Once the request was received by the signal controller, the proposed bus signal priority control mechanism was activated after confirming the location of the bus by the detection of the respective video detector. The information about the adjusted green or red time was also sent to the bus priority equipment to help the bus driver control the bus travelling speed. It is proposed that when the intersection saturation is 0.5, 0.8 and 0.95 respectively, the effects of the bus priority strategies of green time extension, green time insertion and green time advance are evaluated, the results show that these three strategies are only suitable for the intersections with moderate saturation [28]. Considering the impacts of bus priority in coordinated traffic signals [29], the APC strategies of green time extension and green time advance are adopted in this paper, and because the two-way signal coordination scheme was not suitable for the large flow volume environment during the peak hours, the two-way signal coordination scheme was only carried out at two neighboured intersections along Huizhou Avenue during the off-peak period (9:00 -16:00). Therefore, during the tests, the bus priority service was only provided to the abovementioned 5 buses during the off-peak period (9 : 00–16 : 00). Maximally, only one bus priority request would be accepted and conducted in each phase in order to limit the impact on the road traffic.

3.2. Scheme of Traffic Signal Design. The distance of two test intersections is about 1 km, the speed limit for vehicles on Huizhou Avenue is 70km/h, motorized and nonmotorized vehicles are separated from each other through green belts, and the road has less transverse interference because of less crosswalks or community entrances; since there are bus lanes, buses and private cars are driven on different roads, and the traffic of trucks is restricted; the average speed of all vehicles in the road is between 50-60 km/h. Therefore, the designed speed of vehicles used for signal coordination at two adjacent test intersections of Huizhou Avenue is 60km/h, which provides good conditions for signal coordination and bus priority control. The size of the two intersections is appropriate, and the internal distance of the intersections, that is, each the distance between the stop lines and the exit of the intersections, is less than 80 meters, which can ensure that the buses can pass through the intersections quickly and safely when the signal priority control is implemented, thus minimizing the impact on the traffic efficiency of the intersections.Due to the intersection Huizhou Avenue – Jinxiu Avenue with no shopping malls, residential communities, or schools surrounding, pedestrian demand is less; however, there is the pedestrian overpass at the intersection Huizhou Avenue – Ziyun Road, so the influence of pedestrian traffic flow at the two intersections on traffic signals is less and can be ignored. Nonmotor vehicles have the nonmotor vehicle lanes, and nonmotor vehicles follow the traffic signals of the nonconflicting motor vehicles to pass through the intersection; there is also less influence on motor traffic. Therefore, the traffic flow data of private cars and buses are the key data affecting the algorithm model in this paper. In order to facilitate the research, the data of private cars and buses are mainly considered in this paper. The intersection at Huizhou Avenue and Ziyun Road with higher traffic volume is selected as the reference

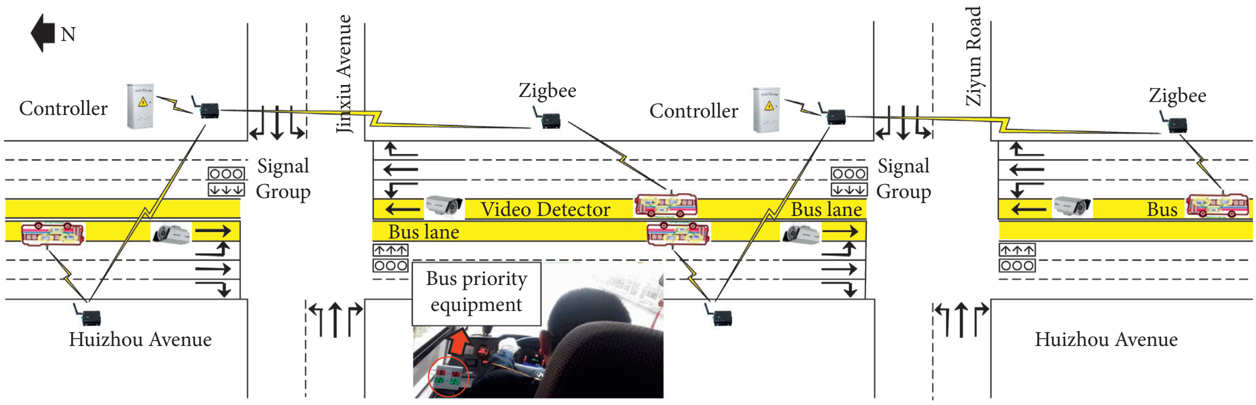
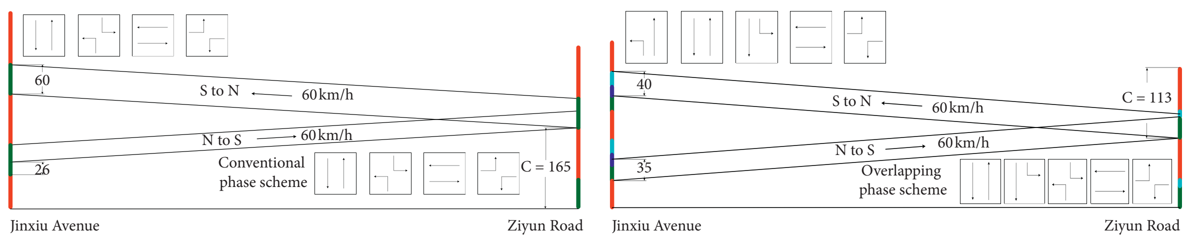
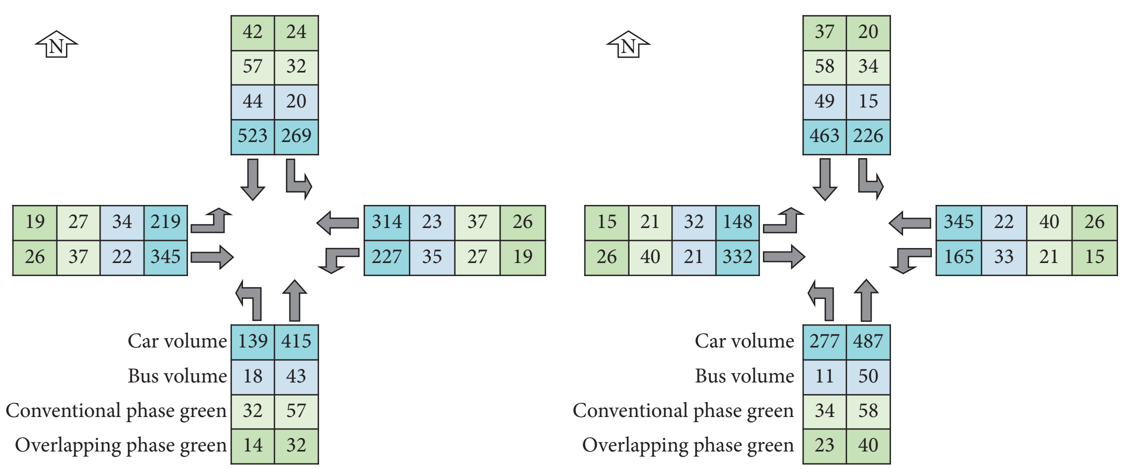


Figure 3: Infrastructure condition for bus signal priority control at the test intersections.



(a) (b)

Figure 4: Designs of the two-way green wave time-distance diagrams and the phase schemes: (a) two-way coordination scheme based on conventional phase and (b) two-way coordination scheme based on the overlapping phase.



(a) (b)

Figure 5: Average hourly traffic volumes during the off-peak period and the designed green time durations. (a) Huizhou Avenue and Ziyun Road intersection. (b) Huizhou Avenue and Jinxiu Avenue intersection.

intersection. Both the conventional signal phase and the overlapping phase are considered in the design of the two-way signal coordination scheme for Huizhou Avenue. The designed two-way green wave time-distance diagrams and phase schemes are shown in Figure 4.

As indicated in Figure 4(a), the conventional phase scheme is a typical symmetrical four-phase scheme, in which the first phase is for the north-south through traffic, the second phase is for the north-south left-turn traffic, the third phase is for the east-west through traffic, and the last phase is for the east-west left-turn traffic. The cycle length is 165 s. In addition to the 4 conventional phases, the signal coordination scheme in Figure 4(b) considers two additional overlapping phases that are for the northbound and the southbound through and left-turn traffic, respectively. The resultant cycle length is 113 s, which is decreased by 31.5% in comparison to the conventional phase scheme. The green wave bandwidth of the conventional phase scheme is

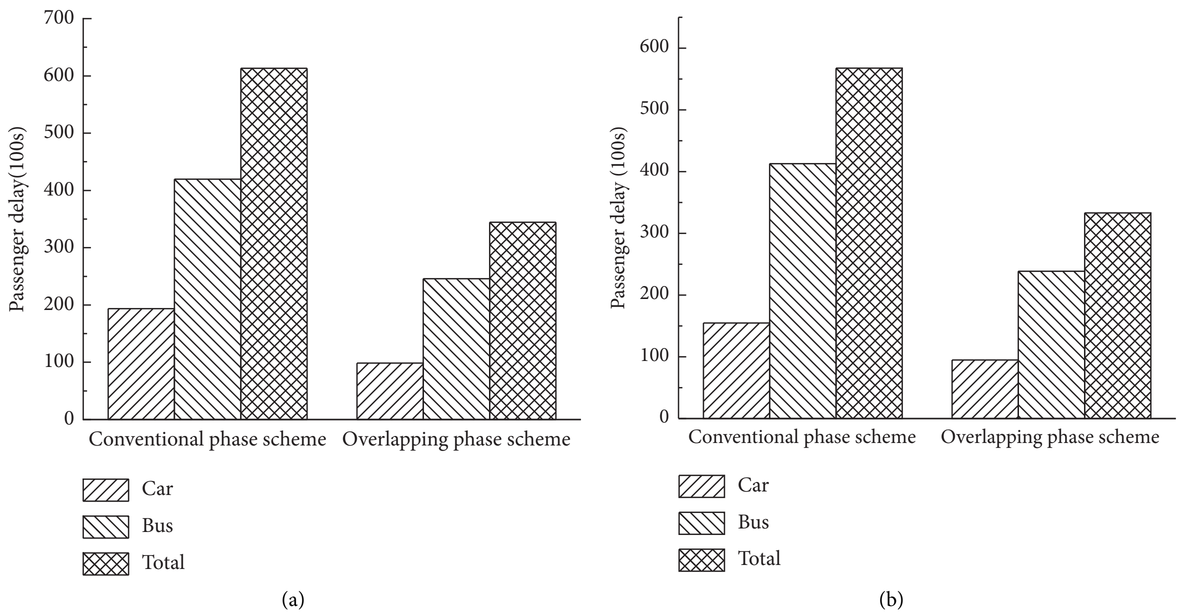


Figure 6: Analysis of total passenger delays at intersections. (a) Huizhou Avenue and Ziyun Road intersection. (b) Huizhou Avenue and Jinxiu Avenue intersection.

Table 1: Part of the test data of bus signal priority control at intersections.

Group	Direction	Arrival time	Control strategy	Before priority control	After priority control
Huizhou Avenue and Ziyun Road intersection					
1	South to north (S to N)	09:12:53	Green advance	met red time for 10s	Green advanced for 5s
2	North to south (N to S)	10:17:11	Green extension	met green time for 3s	Green extended for 22s
3	South to north (S to N)	11:06:05	Green extension	met green time for 12s	Green extended for 13s
Huizhou Avenue and Jinxiu Avenue intersection					
1	South to north (S to N)	09:17:02	Green advance	met red time for 20s	Green advanced for 4s
2	North to south (N to S)	10:12:34	Green extension	met green time for 20s	Green extended for 5s
3	South to north (S to N)	11:10:57	Green advance	met red time for 40s	Green advanced for 11s

Table 2: Traffic survey data and the signal adjustments at intersections.

Controlled direction	q_c (Pcu/s)	q_b (Pcu/s)	S_c (Pcu/s)	S_b (Pcu/s)	g (s)	g' (s)	Δt (s)	r (s)	r' (s)	ΔT (s)
Huizhou Avenue and Ziyun Road intersection										
S to N	0.115	0.012	0.47	0.39	32	45	13	78	65	−13
S To W	0.039	0.005	0.43	0.35	14	11	−3	96	99	3
N to S	0.145	0.012	0.45	0.37	42	52	10	68	58	−10
N to E	0.075	0.006	0.42	0.33	24	18	−6	86	92	6
E to W	0.087	0.006	0.44	0.38	26	22	−4	84	88	4
E to S	0.063	0.01	0.41	0.32	19	16	−3	91	94	3
W To E	0.096	0.006	0.46	0.36	26	22	−4	84	88	4
W to N	0.061	0.009	0.44	0.32	19	16	−3	91	94	3
Huizhou Avenue and Jinxiu Avenue intersection										
S to N	0.135	0.014	0.44	0.37	40	51	11	70	59	−11
S To W	0.077	0.003	0.43	0.33	23	26	3	87	84	−3
N to S	0.129	0.014	0.46	0.39	37	45	8	73	65	−8
N to E	0.063	0.004	0.41	0.34	20	20	0	90	90	0
E to W	0.096	0.006	0.45	0.38	26	18	−8	84	92	8
E to S	0.046	0.009	0.42	0.32	15	12	−3	95	98	3
W To E	0.092	0.006	0.47	0.36	26	18	−8	84	92	8
W to N	0.041	0.009	0.43	0.34	15	12	−3	95	98	3

Table 3: Change of the total passenger delay in each direction at the test intersections (s).

Controlled direction	Huizhou Avenue and Ziyun Road		Huizhou Avenue and Jinxiu Avenue	
	Private car	Bus	Private car	Bus
S to N	−131.6	−445.4	−164.7	−409.1
S to W	9.2	60.5	−29.0	−31.6
N to S	−112.6	−308.8	−86.6	−311.7
N to E	37.1	98.7	0	0
E to W	28.6	13.3	81.7	103.4
E to S	15.6	90.4	9.2	63.2
W to E	32.3	12.1	78.6	98.7
W to N	14.9	87.8	8.3	61.4
Total	−106.5	−391.4	−102.5	−425.7
All	−497.9		−528.2	

obviously uneven (see Figure 4(a)). On the one side, there is a 26 s excess green time in the direction from north to south, which will cause vehicles to start early and encounter a red light. On the other side, the south-to-north green wave bandwidth is too large (60 s) and the green time for the traffic on Jinxiu Avenue will not be used efficiently. In comparison to that the green wave bandwidth of the scheme with the overlapping phases is relatively even. With the proposed overlapping phases, the green time can be fully used. Therefore, the effect of the two-way signal coordination is ideal under the premise of meeting the uneven traffic demand in different directions at intersections.

Furthermore, Figure 5 shows that the northbound through and left-turn traffic volume is higher than the southbound through and left-turn traffic volume. According to conventional phase scheme, the signal timing for the through and left-turn traffic in the north-south direction is calculated according to the higher northbound traffic volume. The flow ratio per cycle is 0.86. According to the signal scheme with the overlapping phases, the signal timing is calculated with the consideration of the different northern and southern inlets. The flow ratio per cycle is 0.79. Due to the difference between the cycle lengths of these two schemes, the respective phase durations also differ from each other. However, the scheme with the overlapping phases can satisfy the traffic demands in all directions, which implicates better traffic control efficiency.

A bus is normally given higher weight in the optimization process since it carries more passengers, e.g., equivalent to 20–50 cars [29]. We can make the assumption that the average number of passengers is 40 per bus and 1.2 per private car, which values are adopted from an NCHRP research regarding bus rapid transit [30], and the total passenger delays at both test intersections are calculated according to equations (11) and (12). The results in Figure 6 show that the total passenger delays with use of the overlapping phase-based signal scheme are significantly reduced when comparing those with use of the conventional signal scheme. The reduction rate is 43.8% and 41.3% at the intersections Huizhou Avenue-Ziyun Road and Huizhou Avenue-Jinxiu Avenue, respectively. This result clearly demonstrates that the overlapping phase-based signal scheme is superior to the conventional signal scheme with regard to the optimal control of isolated intersections and the coordinated control of arterial roads. Therefore, the overlapping phase-based signal scheme is used to further analyze the benefits of bus signal priority under the signal coordination on the main road.

3.3. Bus Signal Priority Control. Following the bus lane arrangement, the bus signal priority control was applied in the north-south direction at the test intersections. The bus priority phase was the coordinated phase 1. During the test period, 5 buses passed through the test intersections 172 times, in which the buses encountered the green time 55 times and the red time 117 times. The bus signal priority control was executed 149 times, in which green time was extended 32 times and advanced 117 times. The selected test data are depicted in Table 1 as reference. All results are calculated with equations (1)–(10). The data in each group ID represent the data of a bus passing two intersections successively. Furthermore, the test data of Group 3 in Table 1 are selected to further analyze the change in total passenger delay after the implementation of bus signal priority control at the two-way coordinated intersections. In this case, the green time extension was executed at the intersection Huizhou Avenue-Ziyun Road, and the green time advance was applied at the intersection Huizhou Avenue-Jinxiu Avenue.

According to equations (13)–(16), when calculating the passenger delay value at the test intersections, it is necessary to survey the arrival rate of private cars and buses and the saturated flow rate data when the vehicles leaving the intersections, and record the time change data of signal lights when the five rapid bus participating in the test implementing signal priority control at intersections. In order to reduce the error, the video detectors installed at the entrance of the intersections are used to detect the traffic flow. The video detectors can accurately identify private cars and buses through the vehicle number plate and model recognition, and the detection accuracy of raffic flow and speed can reach more than 95% after being detected by the authority. The traffic volume and the saturated headway of private cars and buses at each entrance lane of the intersections are detected and counted by the video detectors during the test. The statistical granularity is 15 minutes, and the statistical period is off peak hours (9:00–16:00) for five consecutive working days during the test. After cleaning the abnormal data, the obtained statistical data are summed and averaged to obtain the traffic flow data of each lane in an average hour, of which the traffic flow data are shown in Figure 5. Through further conversion, the arrival rate of private cars and buses and the saturated flow rate data when the vehicles leaving the intersections can be calculated. At the same time, in the statistical period, the controller signal timing change data are monitored when 5 experimental buses pass though the test intersections. The phase green and red time data before and after the implementation of signal priority control at intersections can be accurately obtained, so as to calculate the time change data of signal lights when the signal priority control is implemented at the intersections. The

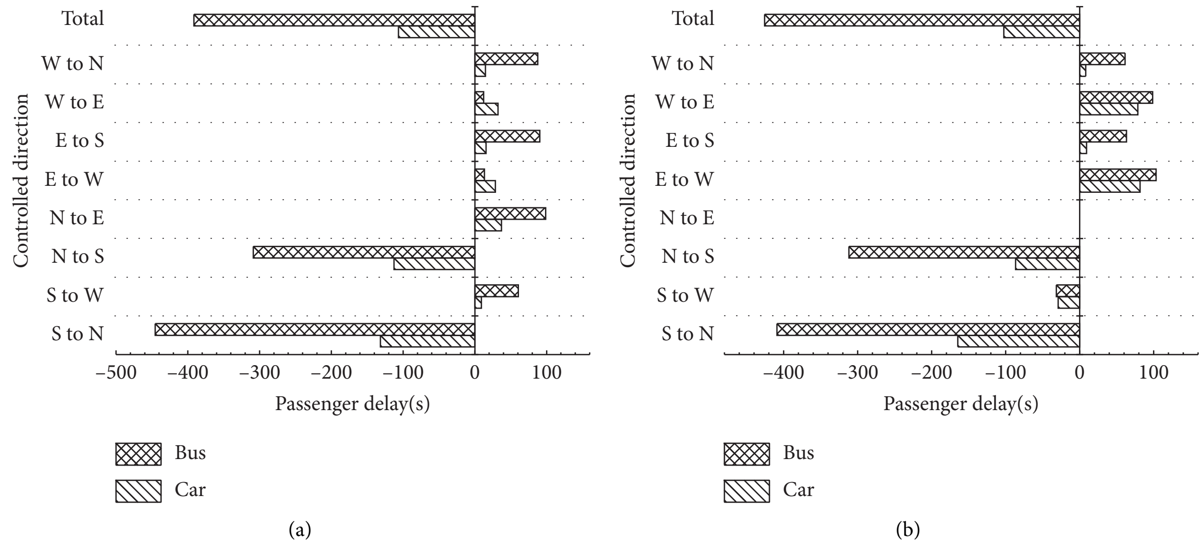


Figure 7: Comparison of the changes of the total passenger delay at the test intersections. (a) Huizhou Avenue and Ziyun Road intersection. (b) Huizhou Avenue and Jinxiu Avenue intersection.

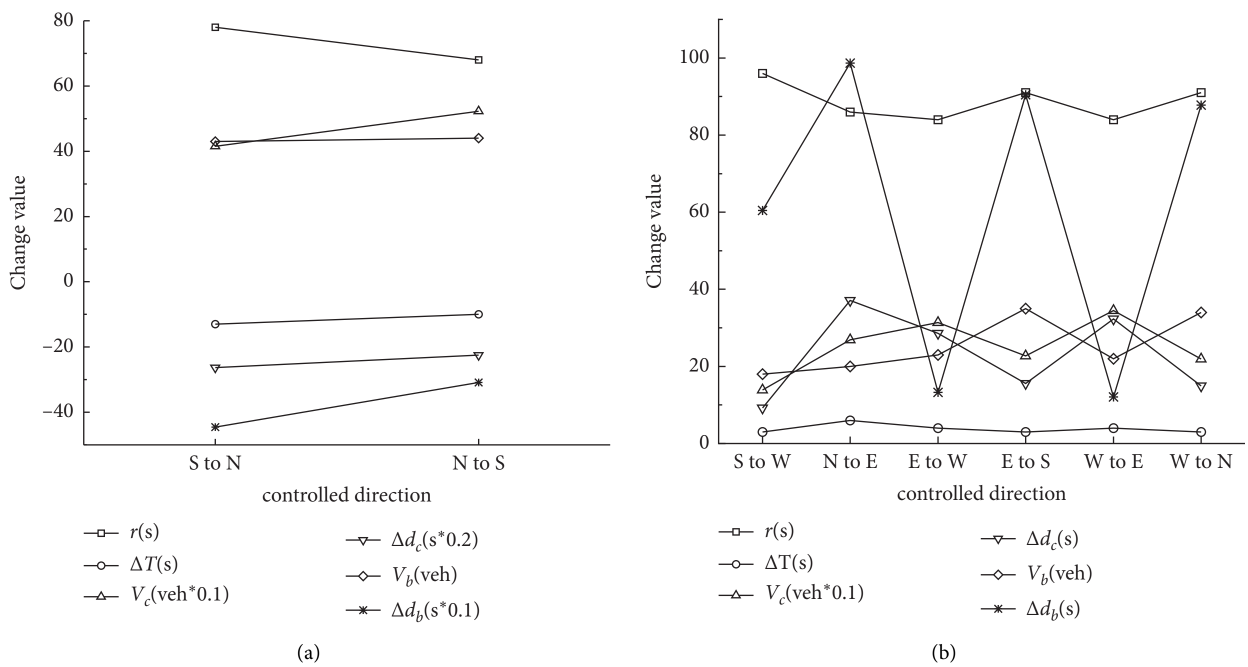


Figure 8: Continued.

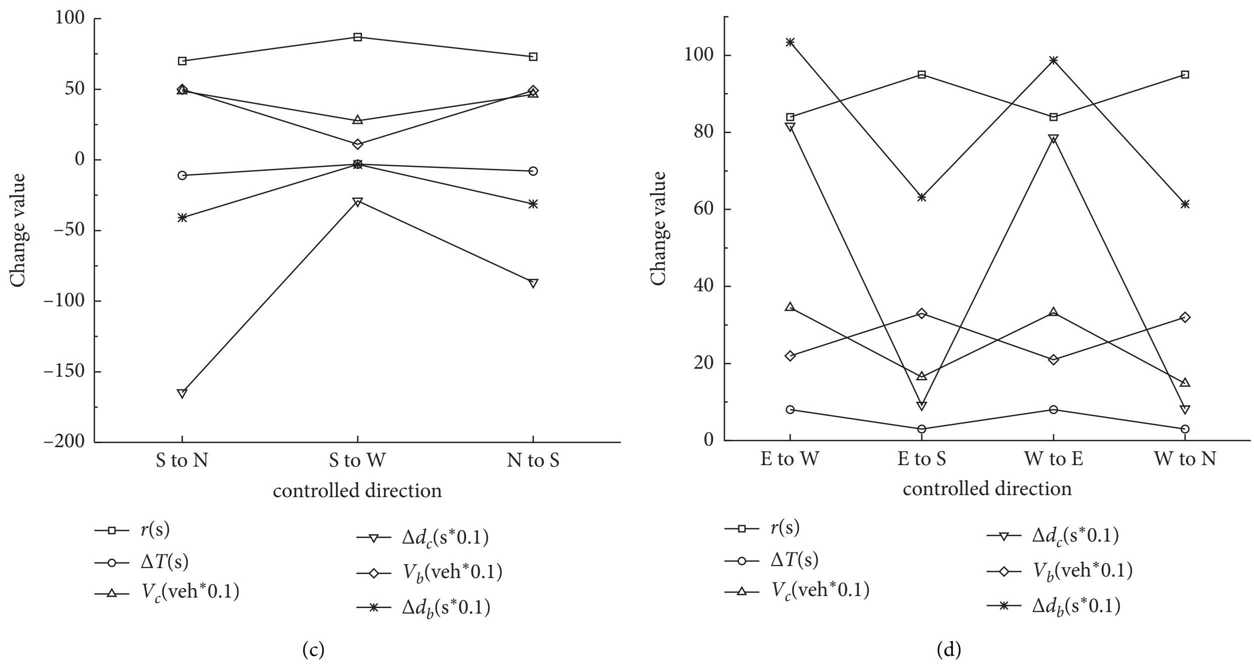


Figure 8: Analysis of the influencing factors related to the change in total passenger delay at intersections. (a) Analysis of decreased value of the passenger delay at Huizhou Avenue and Ziyun Road intersection. (b) Analysis of increased value of the passenger delay at Huizhou Avenue and Ziyun Road intersection. (c) Analysis of decreased value of the passenger delay at Huizhou Avenue and Jinxiu Avenue intersection. (d) Analysis of increased value of the passenger delay at Huizhou Avenue and Jinxiu Avenue intersection.

Table 4: Applicable conditions of the proposed method.

Optimization objective		Maximize the reduction in passenger delay in the bus priority phases	Minimize the increase in passenger delay in the nonbus priority phases
Strategy	Green time extension	Reduce the green time	Decrease the reduction in green time
	Green time advance	Choose the directions with high traffic volume for bus priority	Decrease the reduction in green time
Summary		(i) Allocate the bus priority phases in the directions, which correspond to the directions with large or/and similar flows, such as the north-south direction at the intersection of Huizhou Avenue and Ziyun Road (ii) Use an overlapping phase-based signal control method that can help to reduce the overall signal cycle length and the green time durations of some signal phases (iii) Priority should be given to the buses with high occupancy as far as possible	(i) Minimize the reduction in the green times of the nonbus priority phases (ii) Ensure the basic/necessary green time for the traffic in the nonbus priority phases (iii) If necessary, reduce the green times of the nonbus priority phases evenly and reduce the change in red time

corresponding traffic survey data and the signal adjustment data are indicated in Table 2, where q_c and q_b are the arrival rates of the private cars and the buses, S_c and S_b are the saturation flow rates of the private cars and the buses, g is the green time, g' is the adjusted green time, Δt is the change value of green time, r is the red time, r' is the adjusted red time, and ΔT is the change value of the red time.

With the abovementioned assumption about the average number of passengers carried by buses and private cars and the data in Table 2, the changes in total passenger delays per cycle are calculated with equations (13)–(16) for each controlled direction at the test intersections. As shown in Table 3 and Figure 7, the total passenger delays at the test intersections were significantly decreased by 497.9 s and 528.2 s per cycle (113 s) after adopting the proposed signal scheme and bus priority control. It is also clear to see that the total passenger delays have greatly decreased not only for the buses but also for the private cars. One of the main reasons is that the direction of bus prioritization corresponds to the main traffic flow direction at the test intersections. Under the condition of the fixed cycle length, the green times of the main flow directions were extended when the bus signal priority control was activated. The delays of the private vehicles in the same directions decreased accordingly. In order to ensure the two-way signal coordination and the basic green time duration for private cars, the green time in other directions is less diminished. Therefore, there was only a slight increase in the vehicle delay in the nonprioritized directions, and the overall passenger delay at two intersections was greatly decreased. At the intersection Huizhou Avenue-Ziyun Road, the bus priority was applied in the southbound and northbound through directions, which correspond to the main traffic flow directions. However, at the intersection Huizhou Avenue – Jinxiu Avenue, except for the southbound and northbound through directions, bus priority was also applied in the southbound left-turn direction, where the southbound left-turn direction was not the main traffic flow direction. Therefore, the corresponding reduction in total passenger delay is a little more than that at the intersection Huizhou Avenue – Ziyun Road.

3.4. Analysis of Influencing Factors. Based on the analysis in Section 3.3, the crucial reason for the significant reduction in the total passenger delay after the implementation of the proposed signal scheme and bus signal priority control is that the bus priority directions are correspondent to the main traffic flow directions. In order to clarify the applicable conditions of the proposed method, it is necessary to further analyze the influencing factors. According to equations (13)–(16), the saturation flow rate S_k relates to the road geometry and is therefore quite stable. The arrival rate q_k, which can be converted to traffic volume V_k, the change value of red time ΔT, and the red time r are positively correlated to the change in passenger delay. According to the data in Tables 2 and 3, the relationship between the volume of private cars V_c, the volume of buses V_b, ΔT, and r, the change in the passenger delay of private cars Δd_c, and the change in the passenger delay of buses Δd_b can be further analyzed for identifying the possible influencing factors. The results are illustrated in Figure 8.

Figure 8(a) shows the data comparison regarding the southbound and northbound bus priority directions at the intersection Huizhou Avenue-Ziyun Road. When ΔT is small, r will decrease, V_c will increase, V_b will have little difference, and both the absolute values of Δd_c and Δd_b will decrease. Such phenomenon indicates that the original red time duration has a critical influence on the reduction of the total passenger delay when executing green time extension and the change in the red time duration are limited. Larger red time duration results in smaller green time duration and larger reduction in passenger delay.

Moreover, Figure 8(b) shows the data comparison regarding the nonprioritized directions at the intersection Huizhou Avenue-Ziyun Road. When only little difference in ΔT exists, the change trends of Δd_c and V_c are consistent, Δd_c and r are negatively correlated, and the changes of Δd_b, V_b, and r are then consistent. When observing the flow data in the directions from north to east and from east to west, it is found that a large difference in ΔTresults in the increase in V_c and V_b as well as the decrease in ΔT, Δd_c, and Δd_b. It implies that the change in red time is the main influencing factor, the amount of traffic flows is the second most important factor, and the red time is the secondary factor when applying the green time extension logic. Small change in red time results in small reduction in green time and insignificant increase in passenger delay.

Furthermore, Figure 8(c) shows the data comparison regarding the southbound through, northbound through and left-turn directions at the intersection Huizhou Avenue-Jinxiu Avenue. When there is little difference in ΔT, r increases, V_c and V_b and the absolute values of Δd_c and Δd_b decrease. It implicates that traffic volume is the main factor to influence the change in passenger delay when the green time advance control is executed and the change in red time is limited. The larger the traffic volume is, the larger the reduction in passenger delay will be.

Finally, Figure 8(d) shows the data comparison regarding the nonprioritized directions at the intersection Huizhou Avenue-Jinxiu Avenue. It shows that Δd_c, Δd_b, and ΔT have the consistent trends, Δd_c, Δd_b, and r have the opposite trends, Δd_c and V_c have the consistent trends, and Δd_b and V_b have the opposite trends. When the green time advance control is executed, the change in red time is the main influencing factor with regard to the passenger delay. Traffic volume is then the second important factor. The smaller the change in red time is, the smaller the green time reduction will be. The passenger delay will then increase slightly.

4. Applicability Analysis

Through the test data analysis in Section 3, the following points can be identified.

Under the circumstance that the traffic volumes at the approaches of the given intersection vary greatly, the signal timing optimization scheme with the overlapping phase is obviously better than the scheme with the conventional symmetrical phase. The signal cycle length and total passenger delay at intersections are significantly decreased accordingly. Compared with the conventional phase scheme, the overlapping phase scheme is more conducive to the design of the two-way signal coordination along arterial roads. The bandwidth of the two-way green wave can better correspond to the traffic demand in the coordinated direction(s) so that the respective green time can be used effectively and well signal coordination can be expected. Therefore, when the traffic volume is uneven distribution at intersections on urban arterials, that is, the traffic volume or traffic demand of each inlet at intersections of the urban arterials is quite different, which occurs often in China [31], it is of more practical significance to consider the overlapping phase and apply bus signal priority control under two-way signal coordination. This statement is strongly supported by the field data analysis results in Section 3.

In order to improve the traffic efficiency on urban arterial roads, the bus priority directions of the coordinated phases should be correspondent to the main traffic flow directions. With the implementation of the bus signal priority control in the signal coordination phases, more vehicles can obtain extended green times, which results in a great decrease in delay. While the green times in the nonprioritized directions are protected by the predefined basic green time, less delay will occur. Therefore, the overall delay at intersections along arterial roads can be greatly decreased.

Based on the abovementioned analysis of the influencing factors with regard to the total passenger delay, the applicable conditions of the proposed method are summarized in Table 4.

5. Conclusions

According to the optimization requirements of two-way signal coordination and bus signal priority control on arterial roads, a signal optimization method is proposed with the consideration of the uneven traffic flow distribution at intersections, which occurs often in China. Based on the control logic and the structure of the overlapping phase, the framework of the proposed method covers the multiphase bus signal priority control and the two-way signal coordination on arterial roads. With the respective field test, the bus signal priority control strategy was carried out with 5 buses at the two-way coordinated intersections of Huizhou Avenue in Hefei, China. The effectiveness and applicable conditions of the proposed method are analyzed with use of the total passenger delay at intersections. According to the test data analysis, it is firstly verified that the adoption of overlapping phases can help to further optimize the traffic signal controls at isolated intersections and under the two-way signal coordination along arterial roads, especially under the condition of uneven traffic volume distribution. Moreover, the effectiveness of the proposed overlapping phase-based method is also examined with real test data. Regarding the influencing factors of total passenger delay at intersections, the analysis result pointed out that not all situations are conducive to decreasing passenger delay at intersections. The application of bus signal priority control should be carried out under certain applicable conditions and principles. The following four suggestions are made:

(1) Examine/improve the signal phase design at the analysis intersection according to the collected traffic data, especially when designing an overlapping phase-based signal scheme under the condition of uneven traffic volume distribution at intersections

(2) Use the passenger flow detection technology to obtain the number of passengers in buses and precisely analyze the number of passengers per bus and per direction at the intersection

(3) Mainly set the bus priority phases in the coordinated directions with the main traffic flows according to traffic demand and the bus occupancy rates

(4) Use advanced positioning technologies, such as video, RFID, or GPS, to accurately detect the arrival position of a bus at the given intersection in advance for precisely realize bus signal priority control

Due to the limitation of the practical application requirements and equipment conditions, the field test for bus signal priority control in this paper was only carried out in the southbound and northbound through directions. The analysis of the influencing factors could be further conducted in detail when more data and equipment are available. In addition, the occupancy rates of private cars and buses in different directions at the intersections are currently only the preliminary estimates. Although the calculated total passenger delay in this paper can already reflect the change tendency to a certain degree, the respective accuracy should be further improved.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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