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Research Article

Bus Priority Signal Control Considering Delays of Passengers and Pedestrians of Adjacent Intersections

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In this paper, a bus priority signal control (BPSC) method based on delays of passengers and pedestrians at adjacent intersections, is proposed. The influences of BPSC on passenger and pedestrian delay at adjacent intersections under the condition of coordinated control of green waves are studied. The implementation of BPSC at intersections not only reduces the delay of bus passengers, social vehicle passengers and pedestrians, but also improves the traffic flow of priority buses and social vehicles at downstream intersections. This study takes the green phase extension as an example of the active BPSC strategy, and analyzes three cases of priority vehicles reaching downstream intersection. Firstly, passenger and pedestrian delays at adjacent intersections are calculated under different traffic situations. Secondly, models with the goal of maximizing the reduced total delays are established. Thirdly, three algorithms are used to solve the problem to obtain the optimal signal timing adjustment scheme at upstream intersections. Ultimately, the result shows that the BPSC can effectively reduce pedestrian delays at intersections, protect the rights and interests of pedestrians, reduce the delays of priority vehicles, and maximize the reduced total delay.

1. Introduction

In order to alleviate urban traffic congestion and traffic pollution, it is particularly important and urgent to develop urban transit and to give transit priority accordingly. BPSC is one of the useful measures that has been widely used. For example, BPSC can be used to reduce bus delays to ensure the efficiency of bus operation and to improve the quality of bus service. BPSC is divided into three categories: passive bus priority control, active bus priority control, and adaptive bus priority control. BPSC could not only reduce the delay of buses, but also impact social vehicles and pedestrians at intersections. When a large number of vehicles and pedestrians are at an intersection, if the change of their delays which due to BPSC cannot be fully considered, the bus priority cannot be regarded as successful. Therefore, the impacts of the control scheme on pedestrians and vehicles of the upstream intersection and downstream intersection should be considered. Specifically, in the green wave coordinated control system, when the upstream intersection adopts the BPSC, the bus and some vehicles can smoothly pass through the intersection. However, if the operation of the priority vehicles at the downstream intersection is not taken into consideration, it could increase the delay of pedestrians and vehicles at the downstream intersection. In order to protect the rights and interests of vehicles and pedestrians at adjacent intersections, this paper proposes a BPSC method considering the total delay of vehicles and pedestrians of adjacent intersections.

2. Literature Review

At present, scholars have carried out intensive research on BPSC and pedestrian delay. Christofa et al. considered the total delay on arterials composed of the delay of social vehicles and buses, and presented a real-time signal control system that optimizes signal settings based on minimization of passenger delay on arterials [1]. Zeng et al. proposed a stochastic mixed-integer nonlinear programming (SMINP) model to produce a good transit signal priority (TSP) timing considering the bus stop dwell time and the delay caused by standing vehicle queues [2]. Ghanim and Abu-Lebdeh developed a real-time traffic signal control method integrating traffic signal timing optimization and TSP control using genetic algorithms (GA) and artificial neural networks (ANN) [3]. Wu et al. proposed to optimize the holding time at bus stops, signal timings, and bus speed in order to minimize bus delay so that buses can pass through signalized intersections without stopping [4]. Li and Jin regarded intersection and the downstream bus stop as a control unit and established an optimization model of bus priority green signal duration considering passenger delay at intersection and bus stops [5]. Considering the influence of bus priority strategy on nonpriority phase, Wang et al. established a bi-level programming model with the upper-level model aiming at minimizing the vehicle delay in the nonpriority direction and the lower-level model aiming at minimizing the average passenger delay in the entire intersection [6]. Shu et al. discussed the traffic conditions of bus and social vehicles at near-saturated intersections, and established a model for BPSC based on vehicle delay [7]. Shaaban and Ghanim used VISSIM multimodal microscopic simulation to study the effect of early green and green extension on major urban arterials [8]. According to the operation characteristics of buses and the actual road conditions which aim at the maximum green wave band, Gao established a transit priority control model to obtain the signal timing scheme of arterial intersections and the speed of buses. Consequently she adjusted the speed of buses through the bus detection technology and information transmission technology to control the green wave [9]. Based on the kinematic wave model and vehicle delay, Chow et al. proposed an optimization model aiming at minimizing the bus schedule discrepancies and the total squared headway deviations to adjust the signal timing of arterial intersections. In addition, they also analyzed different control strategies for improving bus service reliability [10, 11]. Hu et al. calculated vehicle delays according to the deviation distribution of vehicle running time, and built a bi-level programming model. The upper level aimed to optimize the efficiency of intersections under the guidance of vehicle speed, while the lower level aimed to optimize the total delay at intersections [12]. Ma et al. took intersection group as the research object, and minimized the travel delay deviation of bus passing through intersection group. For late and early arriving bus, he proposed two optimization strategies "increasing bus delay strategy" and "decreasing bus delay strategy" respectively [13, 14]. Li et al. presented a TSP model that considered the delays at the upstream and downstream intersections along arterial roads based on the strategy of green light extension and red light compression. The model ensured transit priority at upstream intersection and reduced its influence on green wave of social vehicles and downstream intersections [15]. Some scholars have established bi-level optimization models of bus signal priority by analyzing bus delay and person delay. The upper level aims at obtaining optimized public cycle, split and offset, while the lower level optimized the bus signal priority signal with the upper and lower limits of green wave band as constraints [16–18]. In general, most of the existing BPSC methods only considered the queuing and delay of bus and social vehicles at intersections, ignoring the impact of BPSC on pedestrians crossing the street, which easily contribute to increase pedestrian delay.

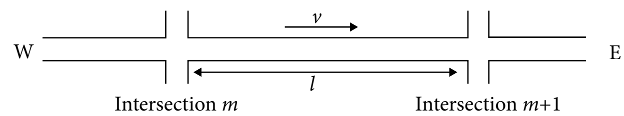

Figure 1: The adjacent intersections.

For the research on the delay of pedestrians, Feng and Pei analyzed moving features and traversing features of vehicles and pedestrians, depicted the sketch map of pedestrians assembling and scattering, and proposed the calculation of average delay and established models according to the delay [19, 20]. Marisamynathan and Vedagiri proposed a pedestrian delay model considering waiting time delay, crossing time delay, and pedestrian-vehicular interaction delay to evaluate the pedestrian level of services at signalized intersections [21]. Ma et al. analyzed the safety and delay of vehicles and pedestrians between the two pedestrian phase patterns, the exclusive pedestrian phase (EPP) and normal two-way crossing (TWC) [22]. For large intersections with center transit lanes, Zhao and Ma studied the passing and stopping situations of pedestrians at intersections (including one-stage crosswalk intersections and two-stage crosswalk intersections), and optimized signal timing scheme according to vehicle and pedestrian delays [23]. Considering pedestrian and vehicle delays at intersections under unsaturated traffic conditions, Yu et al. put forward a method of signal timing for an isolated intersection with one-stage crossing and two-stage crossing [24]. Dai et al. analyzed the pedestrian delay of unsignalized intersections and signalized intersections respectively, and proposed the model considering the delay of signal controlling and vehicle stream disturbance [25]. The previous studies of pedestrian delay only focused on isolated signalized intersections and did not consider multiple intersections with implementing BPSC.

This paper establishes a coordinated control method of BPSC considering passenger delays and pedestrian delays at adjacent intersections. The total changes of delays caused by BPSC are analyzed. The changes include the delay of bus passengers, social vehicle users and pedestrians at the upstream intersection and the increase of stop delay of priority vehicles at downstream intersections.

3. Methodology

3.1. Research Object Setting. Suppose that two adjacent intersections are shown in Figure 1. The direction of the green wave is from west to east and the bus runs from west to east.

3.2. Notation. To facilitate the presentation, all definitions and notations used hereafter are summarized in Table 1.

Table 1: Symbols and parameters.

Symbol	Definition
$g(m,k)$	Green time for the k^{th} phase at intersection m, $k = 1,2,3,4...$
$r(m,k)$	Red time for the k^{th} phase at intersection m, $k = 1,2,3,4...$
$g(m,i)$	Green time for the i^{th} phase at intersection m, i is the priority phase
$r(m,i)$	Red time for the i^{th} phase at intersection m, i is the priority phase
$g(m+1,h)$	Green time for the h^{th} phase at intersection $m+1$, h is the phase when the priority vehicle arrives at intersection $m+1$
$r(m+1,h)$	Red time for the h^{th} phase at intersection $m+1$, h is the phase when the priority vehicle arrives at intersection $m+1$
$r(m,n)$	Red time for the n^{th} phase at intersection m, n is the compensation phase for bus priority
$T_{gover}(m,i)$	The end time of the green light for the i^{th} phase at intersection m
$T^b_{arrival}(m)$	The bus arrival time at m intersection
$\Delta g_t(m,i)$	The extended green time for the i^{th} phase at intersection m
$\varphi(m,m+1)$	The offset between intersection m and intersection $m+1$
$l(m,m+1)$	The distance between intersection m and intersection $m+1$
v	Average speed
C	Cycle length
$\Delta D^b_{de}(m)$	The reduced delay of the bus at intersection m
P^b	Average number of passengers in a bus
$\Delta D^v_{de}(m)$	The reduced delay of the social vehicles at intersection m
P^v	Average number of passengers in a social vehicle
$f(m,j)$	Vehicle arrival rate of j^{th} approach at intersection m
$s(m,j)$	Saturated flow rate of j^{th} approach at intersection m
$\Delta D^p_{de}(m)$	The reduced delay of the pedestrians at intersection m
$f^p(m)$	Average flow of pedestrians at intersection m
$t_l(m,i)$	Green loss time of pedestrians for the i^{th} phase at intersection m
$t_s(m,i)$	Clearance time of pedestrians for the i^{th} phase at intersection m
$\Delta D^v_{in}(m)$	The increased delay of the social vehicles at intersection m
$g_{\min}(m,k)$	Minimum green time for the k^{th} phase at intersection m, $k = 1,2,3,4...$
$g_{\max}(m,k)$	Maximum green time for the k^{th} phase at intersection m, $k = 1,2,3,4...$
$\gamma(m)$	The weight for intersection m
$\Delta D(m)$	The total reduced delay at intersection m

3.3. Analysis of Vehicle Operation. The existing BPSC strategies mainly include three categories: passive priority, active priority, and real-time priority. In practice, most studies focus on strategies of active priority, which have the merits of convenience, flexibility, and simple operation compared to the other strategies. The commonly used active priority strategies include green light extension, shortening red lights, and inserting phase etc. According to the time when the bus arrives at the intersection and the status of traffic lights, different priority control strategies could be adopted.

In order to facilitate the study, this paper makes the following hypotheses.

(1) When the bus arrives at the upstream intersection, the green time is over, that is $T_{gover}(m,i) < T^b_{arrival}(m)$. It is necessary to extend the green time for the i^{th} phase of the upstream intersection to ensure the smooth passage of the bus and the extension of the green light is $\Delta g_t(m,i)$.

(2) The traffic flow is unsaturated and the number of phases and phase sequence in each cycle are unchanged.

(3) The vehicles are moving at a uniform speed at the intersection.

(4) The extended green time for the i^{th} phase is compensated by the n^{th} phase.

If the strategy of green light extension is adopted at the upstream intersection, by analyzing the operation of buses and social vehicles, the following situations shown in Figure 2 will occur when the bus reaches the downstream intersection.

(1) When the upstream bus reaches the downstream intersection, the downstream intersection is in the green phase, that is $g(m,i) + \Delta g_t(m,i) + (l(m,m+1)/v) \bmod (C) \le g(m+1,h) + \varphi(m,m+1)$. The bus can pass through the downstream intersection, and the upstream priority vehicles will not affect the traffic of the downstream intersection.

(2) When the upstream bus reaches the downstream intersection, the downstream intersection is in the red phase.The bus and the tail of the fleet are blocked at the downstream intersection, that is $g(m,i) + (l(m,m+1)/v) \bmod (C) < g(m+1,h) + \varphi(m, m+1) < g(m,i) + \Delta g_t(m,i) + (l(m,m+1)/v)\ mod\ (C)$.

(3) When the upstream bus reaches the downstream intersection, the downstream intersection is in red

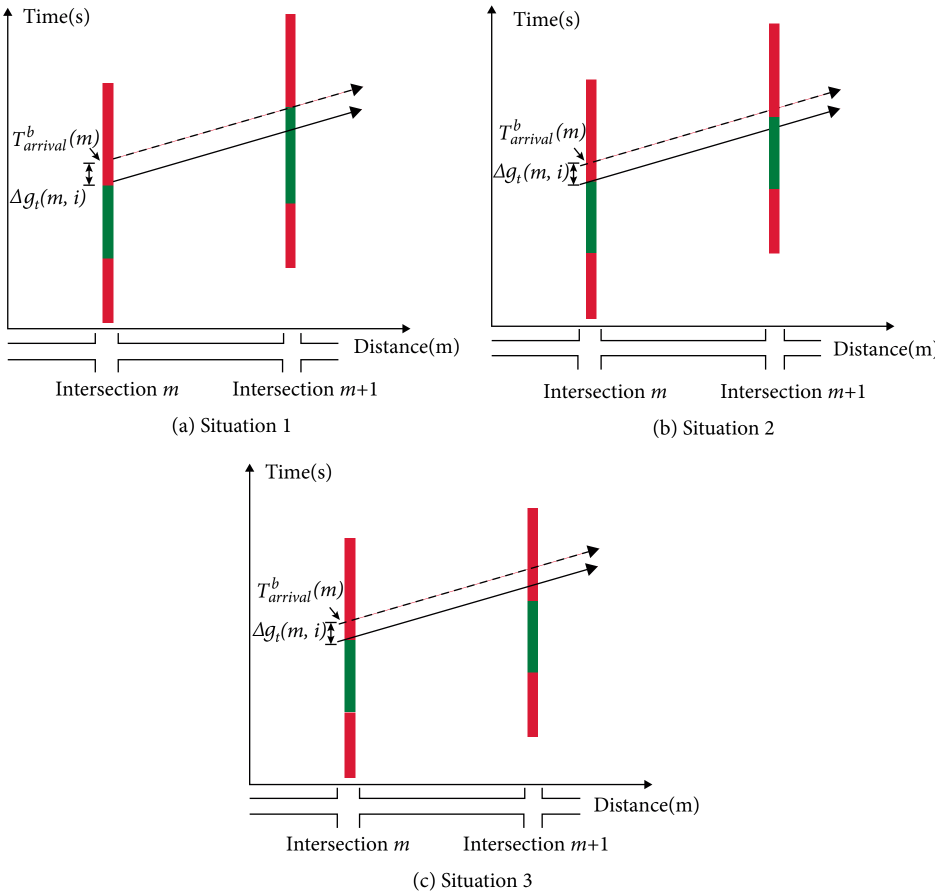

Figure 2: Implementation of the green light extension strategy.

phase, and all the vehicles are detained at the downstream intersection, that is $g(m+1,h) + \varphi(m,m+1) \leq g(m,i) + (l(m,m+1)/v) \bmod (C) < C + \varphi(m,m+1)$.

4. BPSC Process

The control system could obtain the arrival time of the bus through the detector at the upstream intersection, establish models to analyze the delay of pedestrians and vehicles at the upstream and downstream intersections, and obtain the specific priority schemes of the upstream intersection. The specific control process is shown in Figure 3.

Step 1: When the detector detects the bus, the system predicts that the bus will arrive at the stop line at the upstream intersection at time $T^b_{arrival}(m)$.

Step 2: According to the arrival time of the bus and the end of the green light at the upstream intersection, the system evaluates whether the signal timing scheme should be adjusted. If $T_{gover}(m,i) \geq T^b_{arrival}(m)$, keep the timing scheme, otherwise the green time should be extended by $\Delta g_t(m,i)$.

Step 3: According to the average flow of pedestrians and traffic at the intersection, the system analyzes the delay of pedestrians and passengers at the intersection after the green light extension at the upstream intersection.

Step 4: When the green phase of the upstream intersection is extended by $\Delta g_t(m,i)$, the system will analyze the hindered status of the upstream vehicles reaching the downstream intersection and calculate the delay of vehicles and pedestrians at the upstream and downstream intersection. Then, the system will establish models to obtain the optimal timing scheme of the upstream intersection.

Step 5: If the bus could arrive at the upstream intersection within the extended green time, which is $T_{gover}(m,i) < T^b_{arrival}(m) \leq T_{gover}(m,i) + \Delta g_t(m,i)$, the signal timing scheme needs to be adjusted. Otherwise if $T_{gover}(m,i) + \Delta g_t(m,i) < T^b_{arrival}(m)$, the original signal timing plan should be used.

5. BPSC Delay Model

This paper takes the upstream and downstream intersections with large crossing pedestrian volume as an example. To ensure the traffic conditions of the crossing pedestrians, models aiming at maximizing the reduced total delay are developed by considering the delays of bus passengers, social vehicle users and crossing pedestrians at upstream and downstream intersections. In order to calculate the delay of the bus, it is assumed that the bus will arrive at the intersection by the end of the extended green light.

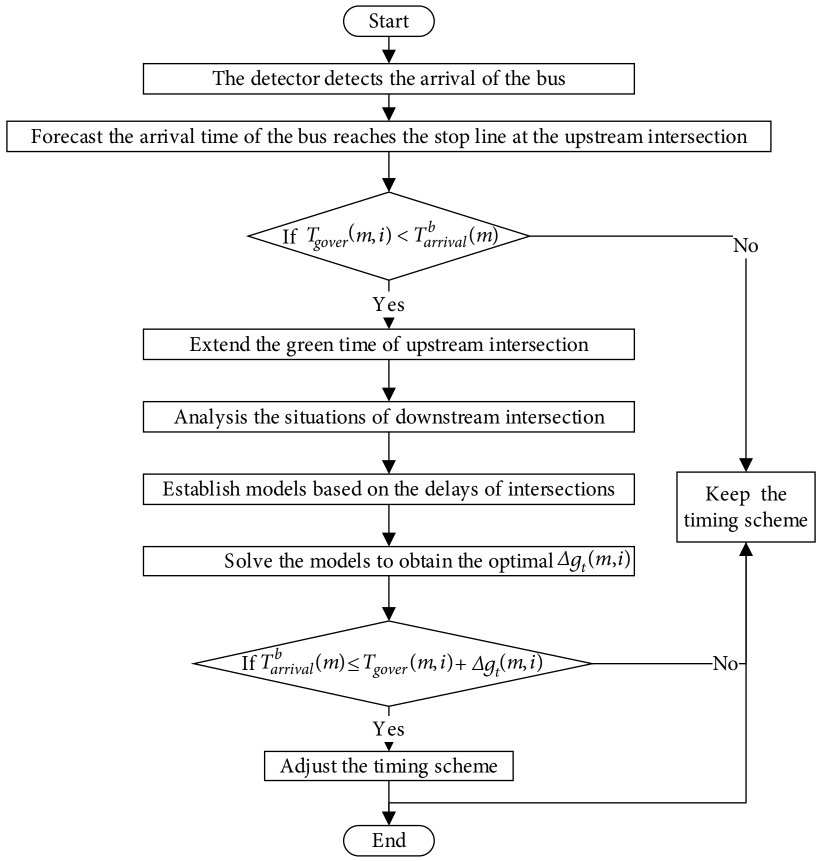

FIGURE 3: Flow chart of BPSC.

5.1. Analysis of Delay at Upstream Intersection. When the green phase extension strategy is adopted at the upstream intersection, the green time for priority phase is extended and the green time for nonpriority phase is shortened. Hence, the delay of priority phase is reduced, which includes the delays of bus passengers, social vehicle users and crossing pedestrians. The specific analysis is as follows:

(1) By adopting the green light extension strategy, buses can pass the intersection without stopping, which reduces the delay of stopping and waiting, so the reduced delay of bus passengers can be calculated by Equation (1):

$$\Delta D^{b}_{de}(m) = P^{b}\left[r(m,i) - \Delta g_t(m,i)\right]. \quad (1)$$

(2) The reduced delay of social vehicle users is shown in Figure 4. Social vehicles can pass the intersection without stopping in the extended green time $\Delta g_t(m,i)$. The reduced delay of passengers of social vehicles can be calculated by Equation (2):

$$\Delta D^{v}_{de}(m) = P^{v}\sum_{j}\frac{\Delta g_t(m,i)\cdot f(m,j)\cdot s(m,j)/3600}{2\left[s(m,j) - f(m,j)\right]} \cdot \left[2r(m,i) - \Delta g_t(m,i)\right]. \quad (2)$$

(3) The reduced delay of crossing pedestrians is shown in Figure 5. The waiting time of pedestrians is reduced by $\Delta g_t(m,i)$, and the reduced delay can be calculated by Equation (3):

$$\Delta D^{p}_{de}(m) = \frac{f^{p}(m)}{3600} \times \frac{\left[t_l(m,i) + r(m,i) + t_s(m,i)\right]\left[2t_l(m,i) + 2r(m,i) - \Delta g_t(m,i)\right]\Delta g_t(m,i)}{2\left[t_l(m,i) + r(m,i)\right]}. \quad (3)$$

The delay of nonpriority phase increases, which includes the delays of social vehicle users and crossing pedestrians. The specific analysis is as follows:

(1) The increased delay of social vehicles is shown in Figure 6. The red light time is extended and the waiting time of vehicles increases. The vehicles that could have passed need to stop and wait. Therefore, the increased delay of social vehicles is represented by the area of shadows in the Figure 6, and the increased delay of users can be calculated by Equation (4):

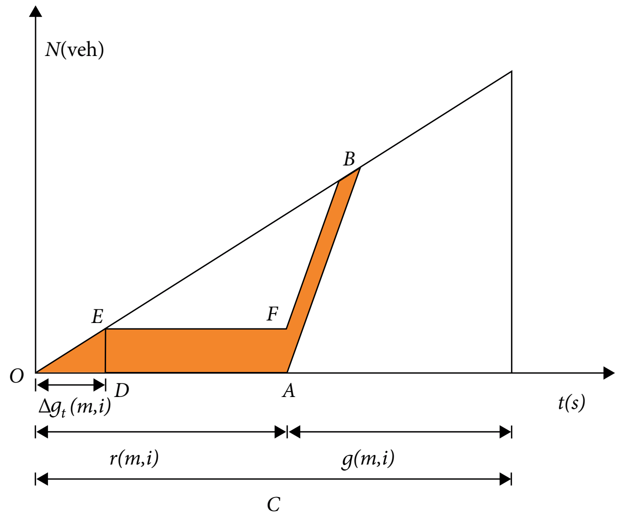

Figure 4: Analysis of social vehicle delay for priority phase [26].

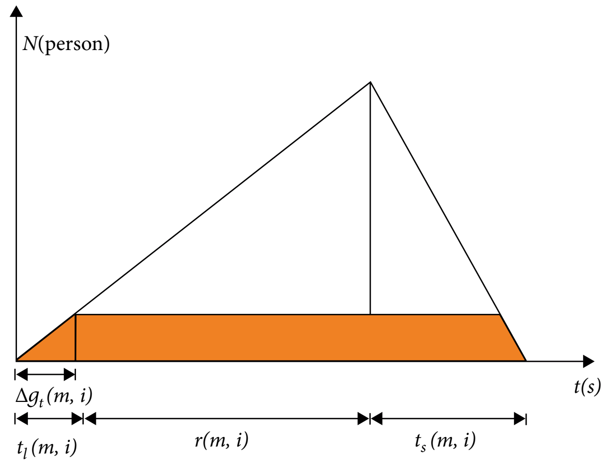

Figure 5: Priority phase pedestrian delay analysis.

$$\Delta D_{in}^{v}(m) = P^{v}\sum_{j}\frac{\Delta g_t(m,i)\cdot f(m,j)/3600}{2[1-(f(m,j)/s(m,j))]}\cdot[2r(m,n)+\Delta g_t(m,i)]. \tag{4}$$

(2) The increased delay of crossing pedestrians is represented by the area of shadows in the Figure 7, which can be calculated by Equation (5):

$$\Delta D_{in}^{p}(m) = \frac{f^{p}(m)}{3600}\times\frac{[t_l(m,n)+r(m,n)+t_s(m,n)][2t_l(m,n)+2r(m,n)+\Delta g_t(m,i)]\Delta g_t(m,i)}{2[t_l(m,n)+r(m,n)]}. \tag{5}$$

5.2. Analysis of Delay at Downstream Intersection. When the green light extension strategy is adopted at the upstream intersection, the analysis of delay at the downstream intersection is discussed according to three cases in Figure 2.

(1) When the priority vehicles reach the downstream intersection, as described in situation 1 of Figure 2, it is during green phase and the vehicles can directly pass through. The total delay model of the upstream and downstream intersection is established as Equation (6).

$$\max \Delta D = \Delta D(m) = \left\{\Delta D_{de}^{b}(m), \Delta D_{de}^{v}(m)-\Delta D_{in}^{v}(m), \Delta D_{de}^{p}(m)-\Delta D_{in}^{p}(m)\right\},$$
$$\left.\begin{array}{l} g(m,i)+\Delta g_t(m,i)+\dfrac{l(m,m+1)}{v} \bmod (C) \le g(m+1,i)+\varphi(m,m+1) \\ g_{\min}(m,k)\le g(m,k)\le g_{\max}(m,k); k=1,2,3,4\ldots\ldots \\ \Delta g_t(m,i)\ge 0 \end{array}\right\} s.t. \tag{6}$$

(2) When the priority vehicles reach the downstream intersection, as described in situation 2 of Figure 2, some of the priority social vehicles can pass through the intersection, but the bus and the tail of the social vehicles are hindered. The delays of downstream intersection increase, and the increased delays are as follow.

The increased delay of bus passengers can be calculated by Equation (7)

$$\Delta D_{in}^{b}(m+1) = P^{b}\left\{C+\varphi(m,m+1) - \left[g(m,i)+\Delta g_t(m,i)+\frac{l(m,m+1)}{v} \bmod (C)\right]\right\}. \tag{7}$$

The increased delay of social vehicle passengers is represented by the area of shadows in Figure 8, which can be calculated by Equation (8)

$$\Delta D_{in}^{v}(m+1) = P^{v}\sum_{j}\frac{[g(m,i)+\Delta g_t(m,i)+(l(m,m+1)/v) \bmod (C)-g(m+1,h)-\varphi(m,m+1)]f(m,j)\cdot s(m+1,j)/3600}{2[s(m+1,j)-f(m,j)]}$$
$$\times\left\{2r(m+1,h)-\left[g(m,i)+\Delta g_t(m,i)+\frac{l(m,m+1)}{v} \bmod (C)\right]-g(m+1,h)-\varphi(m,m+1)\right\}. \tag{8}$$

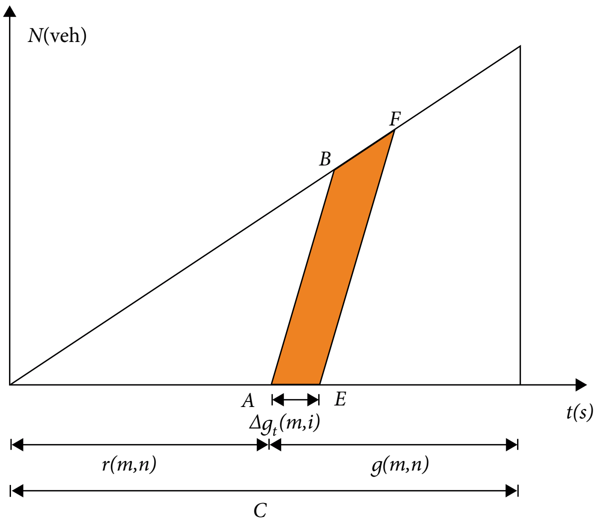

Figure 6: Analysis of nonpriority phase social vehicle delay.

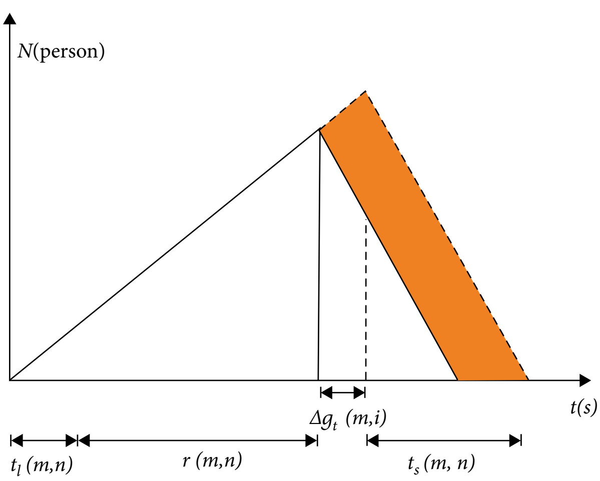

Figure 7: Analysis of nonpriority phase crossing pedestrian delay.

The total delay model of the upstream and downstream intersection is established as Equation (9).

$$\left.\begin{aligned}\max \Delta D &= \left\{\Delta D^b, \Delta D^v, \Delta D^p\right\}\\ \Delta D^b &= \gamma(m)\Delta D^b_{de}(m) + \gamma(m+1)\left[-\Delta D^b_{in}(m+1)\right]\\ \Delta D^v &= \gamma(m)\left[\Delta D^v_{de}(m) - \Delta D^v_{in}(m)\right] + \gamma(m+1)\left[-\Delta D^v_{in}(m+1)\right]\\ \Delta D^p &= \Delta D^p_{de}(m) - \Delta D^p_{in}(m)\end{aligned}\right\},$$
$$\left.\begin{aligned}&g(m,i) + \frac{l(m,m+1)}{v} \bmod (C) < g(m+1,h) + \varphi(m,m+1)\\ &< g(m,i) + \Delta g_t(m,i) + \frac{l(m,m+1)}{v} \bmod (C)\\ &g_{\min}(m,k) \le g(m,k) \le g_{\max}(m,k); k = 1,2,3,4\ldots\ldots\\ &\Delta g_t(m,i) \ge 0\end{aligned}\right\} s.t. \tag{9}$$

(3) When the priority vehicles reach the downstream intersection, as described in situation 3 of Figure 2, the bus and all the priority social vehicles are hindered. The delays of downstream intersection increase, and the increased delays are as follow.

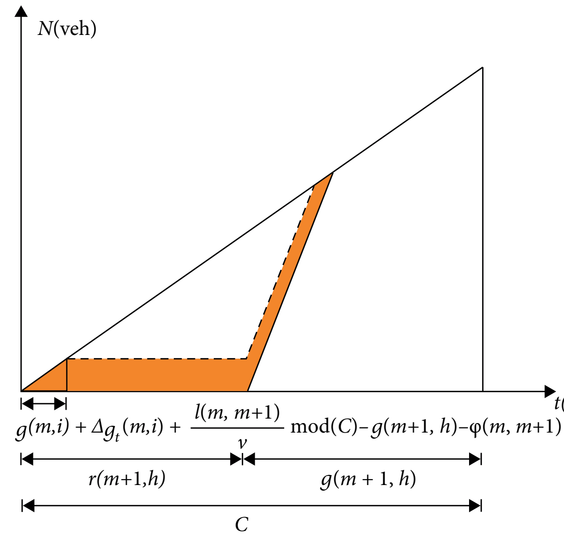

Figure 8: Analysis of partial priority vehicle delay at downstream intersection.

The increased delay of bus passengers can be calculated by Equation (10):

$$\Delta D^b_{in}(m+1) = P^b\left\{C + \varphi(m,m+1) - \left[g(m,i) + \Delta g_t(m,i) + \frac{l(m,m+1)}{v} \bmod (C)\right]\right\}. \tag{10}$$

The increased delay of social vehicle passengers is represented by the area of shadows in Figure 9, which can be calculated by Equation (11):

$$\Delta D^v_{in}(m+1) = P^v \sum_j \frac{\Delta g_t(m,i)\cdot f(m,j)\cdot s(m+1,j)/3600}{2\left[s(m+1,j) - f(m,j)\right]} \times\left\{2\left[C + \varphi(m,m+1) - \left(g(m,i) + \frac{l(m,m+1)}{v} \bmod (C)\right)\right] - \Delta g_t(m,i)\right\}. \tag{11}$$

The total delay model considering delays at the upstream and downstream intersection is established as Equation (12).

$$\left.\begin{aligned}\max \Delta D &= \left\{\Delta D^b, \Delta D^v, \Delta D^p\right\}\\ \Delta D^b &= \gamma(m)\Delta D^b_{de}(m) + \gamma(m+1)\left[-\Delta D^b_{in}(m+1)\right]\\ \Delta D^v &= \gamma(m)\left[\Delta D^v_{de}(m) - \Delta D^v_{in}(m)\right] + \gamma(m+1)\left[-\Delta D^v_{in}(m+1)\right]\\ \Delta D^p &= \Delta D^p_{de}(m) - \Delta D^p_{in}(m)\end{aligned}\right\},$$
$$\left.\begin{aligned}&g(m+1,h) + \varphi(m,m+1) \le g(m,i) + \frac{l(m,m+1)}{v} \bmod (C) < C + \varphi(m,m+1)\\ &g_{\min}(m,k) \le g(m,k) \le g_{\max}(m,k); k = 1,2,3,4\ldots\ldots\\ &\Delta g_t(m,i) \ge 0\end{aligned}\right\} s.t. \tag{12}$$

5.3. Optimization Algorithms. The models mentioned above are multi-objective optimization models. These models are solved using three different algorithms namely, the multi-objective genetic algorithm function gamultiobj, multi-objective particle swarm optimization (MOPSO) and goal attainment method function fgoalattain.

Table 2: Basic parameters of intersections during peak period.

Intersection	Direction		Vehicle volume (pcu·h^{-1})	Saturation flow rate (pcu·h^{-1})	Pedestrian volume (person·h^{-1})
Intersection m	East	Straight going	368	2000	1152
		Left turn	92	1500	
	West	Straight going	344	2000	1116
		Left turn	116	1500	
	South	Straight going	640	2400	1460
		Left turn	189	1500	
	North	Straight going	656	2400	1480
		Left turn	177	1500	

Genetic algorithm is a search algorithm to solve the optimization problem, which draws lessons from the phenomena of heredity, mutation, natural selection and hybridization in the process of biological evolution. The algorithm of function gamultiobj is a variant of NSGA-II (Nondominated sorting and sharing genetic algorithm II), which can effectively solve multi-objective optimization problems.

Particle swarm optimization (PSO) is a random search algorithm based on group cooperation, which is developed by simulating the foraging behavior of birds. The multi-objective particle swarm optimization algorithm is based on the single objective particle swarm optimization and Pareto optimization, so that the particle swarm optimization algorithm can deal with the multi-objective problems.

Function fgoalattain is a multi-objective optimization function in MATLAB. The algorithm used in this function is goal attainment method. The principle of goal attainment method to solve the multi-objective model is to find the minimum deviation between all objective functions and goals, so as to obtain the extreme value of the objective function. The goal of this method is clear and the calculation speed is fast, but it may only give the local optimal solutions.

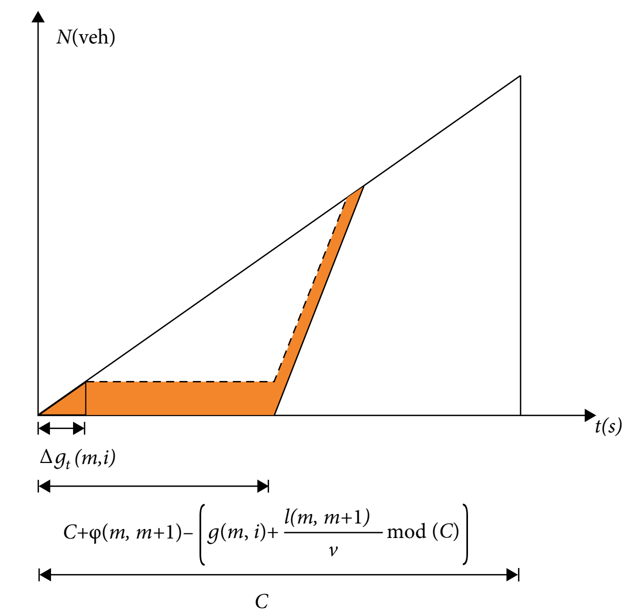

Figure 9: Analysis of all priority vehicle delay at downstream intersection.

6. Case Study

In order to illustrate the effectiveness of the BPSC model considering the delays of passengers and pedestrians at adjacent intersections, the adjacent intersections on Shenghe Road in Chengdu, China are used as an example. The intersection of Shenghe Road and the northern section of Yizhou Avenue is regarded as upstream intersection m. The intersection of Shenghe Road and Duhui Road is regarded as downstream intersection $m+1$. These intersections are close to the Chengdunan Railway Station. The bus flow and the pedestrian flow are large. The traffic parameters of upstream intersections during peak and nonpeak periods are shown in Tables 2 and 3. The saturated flow rates of both east and west straight approach at the intersection $m+1$ are 2000 (pcu·h^{-1}).

Assuming the two intersections are coordinated control intersections, the signal timing scheme is shown in Figure 10. The cycle is 160 s and offset is 15 s. Right-turn vehicles are not controlled by signals. The average clearance time of crossing pedestrians is 20 s, and the average loss of pedestrians' crossing time is 3 s. $\gamma(m)$ is 0.6, $\gamma(m+1)$ is 0.4. The distance between intersections is 300 m.

In order to reduce the impact on straight traffic, after prolonging the green time of the east-west straight phase of upstream intersection, the green time of the left-turn phase in the north-south direction would be appropriately reduced to compensate. The speed limit of urban roads is 60 km/h. If the fleet can run at an average speed of 60 km/h, Situation 1 and Situation 2 shown in Figure 2 may appear after the green light extension of the upstream intersection. If the fleet runs slowly, the average speed can only reach 50 km/h, Situation 3 may appear. The three situations are discussed below.

(1) Situation 1, when $g(m,i) + \Delta g_t(m,i) + (l(m,m+1)/v) \bmod (C) \leq g(m+1,h) + \varphi(m,m+1)$, the priority vehicles can pass through the intersection $m+1$ without stopping. A delay model is developed, and the three algorithms are used to obtain the solutions. The results of the model in situation 1 during the peak period are shown in Table 4. The green light extension time obtained by three algorithms are 2.86 s, 2.89 s, and 2.70 s, respectively.

The results of the model in situation 1 during the nonpeak period are shown in Table 5. The green light

Table 3: Basic parameters of intersections during nonpeak period.

Intersection	Direction		Vehicle Volume (pcu·h^{-1})	Saturation flow rate (pcu·h^{-1})	Pedestrian volume (person·h^{-1})
Intersection m	East	Straight going	276	2000	683
		Left turn	65	1500	
	West	Straight going	248	2000	688
		Left turn	80	1500	
	South	Straight going	460	2400	810
		Left turn	150	1500	
	North	Straight going	478	2400	821
		Left turn	128	1500	

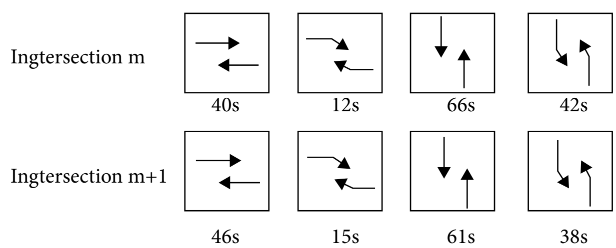

Figure 10: Coordinated control timing scheme.

Table 4: Results of delay model in situation 1 during the peak period.

Algorithm	Gamultiobj	MOPSO	Fgoalattain
Delay of bus passengers (s)	−3514.07	−3513.3	−3519.14
Delay of vehicle users (s)	−126.36	−127.5	−119.14
Delay of crossing pedestrian (s)	−54.82	−55.3	−51.92
$\Delta g_t(m,i)$ (s)	2.86	2.89	2.70
Computation time (s)	0.298	0.553	0.262

Table 5: Results of delay model in situation 1 during the nonpeak period.

Algorithm	Gamultiobj	MOPSO	Fgoalattain
Delay of bus passengers (s)	−3564.55	−3569.32	−3567.18
Delay of vehicle users (s)	35.77	30.94	33.11
Delay of crossing pedestrian (s)	−18.20	−15.82	−16.89
$\Delta g_t(m,i)$ (s)	1.18	1.02	1.09
Computation time (s)	0.369	0.550	0.266

Table 6: Results of delay model in situation 2 during the peak period.

Algorithm	Gamultiobj	MOPSO	Fgoalattain
Delay of bus passengers (s)	−727.01	−728.48	−729.47
Delay of vehicle users (s)	−96.92	−94.71	−93.21
Delay of crossing pedestrian (s)	−85.37	−81.87	−79.47
$\Delta g_t(m,i)$ (s)	4.83	4.59	4.42
Computation time (s)	0.465	0.547	0.262

Table 7: Results of delay model in situation 2 during the nonpeak period.

Algorithm	Gamultiobj	MOPSO	Fgoalattain
Delay of bus passengers (s)	−727.24	−729.23	−729.97
Delay of vehicle users (s)	−62.43	−60.64	−59.97
Delay of crossing pedestrian (s)	−66.36	−62.42	−60.92
$\Delta g_t(m,i)$ (s)	4.79	4.46	4.34
Computation time (s)	0.383	0.564	0.250

Table 8: Results of delay model in situation 3 during the peak period.

Algorithm	Gamultiobj	MOPSO	Fgoalattain
Delay of bus passengers (s)	−770.35	−771.07	−770.65
Delay of vehicle users (s)	−51.12	−49.98	−50.65
Delay of crossing pedestrian (s)	−85.04	−83.34	−84.33
$\Delta g_t(m,i)$(s)	4.81	4.69	4.76
Computation time (s)	0.401	0.530	0.261

Table 9: Results of delay model in situation 3 during the nonpeak period.

Algorithm	Gamultiobj	MOPSO	Fgoalattain
Delay of bus passengers (s)	−771.10	−771.13	−770.91
Delay of vehicle users (s)	−30.73	−30.70	−30.91
Delay of crossing pedestrian (s)	−65.06	−65.00	−65.44
$\Delta g_t(m,i)$ (s)	4.68	4.68	4.71
Computation time (s)	0.367	0.545	0.263

extension time obtained by three algorithms are 1.18 s, 1.02 s, and 1.09 s, respectively.

(2) Situation 2, when $g(m,i) + (l(m,m+1)/v) \bmod (C) < g(m+1,h) + \varphi(m,m+1) < g(m,i) + \Delta g_t(m,i) + (l(m,m+1)/v) \bmod (C)$, the bus and the tail of the fleet are blocked at the intersection $m+1$. A delay model is developed, and the three algorithms are used to obtain the solutions. The results of the model in situation 2 during the peak period are shown in Table 6. The green light extension time obtained by three algorithms are 4.83 s, 4.59 s, and 4.42 s, respectively.

Table 10: Comparison of delay of two control methods during peak period.

Situation	Consider pedestrian delay	Green extended (s)	Bus passengers delay variation (s)	Vehicle users delay variation (s)	Pedestrian delay variation (s)
1	Yes	2.86	−3514.07	−126.36	−54.82
	No	2.61	−3521.66	−115.55	−50.47
2	Yes	4.83	−727.01	−96.92	−85.37
	No	4.54	−728.75	−94.30	−81.22
3	Yes	4.81	−770.35	−51.12	−85.04
	No	4.48	−772.35	−47.95	−80.25

Table 11: Comparison of delay of two control methods during nonpeak period.

Situation	Consider pedestrian delay	Green extended (s)	Bus passengers delay variation (s)	Vehicle users delay variation (s)	Pedestrian delay variation (s)
1	Yes	1.18	−3564.55	35.77	−18.20
	No	1.04	−3568.70	31.56	−16.13
2	Yes	4.79	−727.24	−62.43	−66.36
	No	3.11	−737.32	−52.95	−45.35
3	Yes	4.68	−771.10	−30.73	−65.06
	No	3.50	−778.23	−23.69	−50.35

The results of the model in situation 2 during the nonpeak period are shown in Table 7. The green light extension time obtained by three algorithms are 4.79 s, 4.46 s, and 4.34 s, respectively.

(3) Situation 3, when $g(m+1,h)+\varphi(m,m+1)\le g(m,i)+(l(m,m+1)/v) \bmod (C) < C+\varphi(m,m+1)$, the bus and all the priority vehicles are blocked at intersection $m+1$. A delay model is developed, and the three algorithms are used to obtain the solutions. The results of the model in situation 3 during the peak period are shown in Table 8. The green light extension time obtained by three algorithms are 4.81 s, 4.69 s, and 4.76 s, respectively.

The results of the model in situation 3 during the nonpeak period are shown in Table 9. The green light extension time obtained by three algorithms are 4.68 s, 4.68 s, and 4.71 s, respectively.

Considering the results of three algorithms, the calculation speed of function gamultiobj and function fgoalattain are faster than that of MOPSO. Taking the result of genetic algorithm as an example, the effect of BPSC considering the delay of crossing pedestrians and the effect of conventional control without considering pedestrians are compared in Tables 10 and 11.

(1) Situation 1, during the peak period, if delay of crossing pedestrians is not taken into consideration, the green time at intersection m can be extended by 2.61 s. However, if delay of crossing pedestrians is considered, the green time at intersection m can be extended by 2.86 s. The bus delay increases less than 1%, while the delays of social vehicles and pedestrians are both reduced by 9%. During the nonpeak period, if delay of crossing pedestrians is not taken into consideration, the green time at intersection m can be extended by 1.04 s. But, if delay of crossing pedestrians is considered, the green time at intersection m can be extended by 1.18 s. The delays of bus and social vehicles increase, while pedestrian delay is reduced by 13%.

(2) Situation 2, during the peak period, if delay of crossing pedestrians is not taken into consideration, the green time at intersection m can be extended by 4.54 s. However, if delay of crossing pedestrians is considered, the green time at intersection m can be extended by 4.83 s. The bus delay increases less than 1%, while delays of social vehicles and pedestrians are reduced by 3% and 5% respectively. During the nonpeak period, if delay of crossing pedestrians is not taken into consideration, the green time at intersection m can be extended by 3.11 s. But, if delay of crossing pedestrians is considered, the green time at intersection m can be extended by 4.79 s. The bus delay increases by 1%, while delays of social vehicles and pedestrians are reduced by 18% and 46% respectively.

(3) Situation 3, during the peak period, if delay of crossing pedestrians is not taken into consideration, the green time at intersection m can be extended by 4.48 s. However, if delay of crossing pedestrians is considered, the green time at intersection m can be extended by 4.81 s. The bus delay increases less than 1%, while delays of social vehicles and pedestrians are reduced by 7% and 6% respectively. During the nonpeak period, if delay of crossing pedestrians is not taken into consideration, the green time at intersection m can be extended by 3.50 s. But, if delay of crossing pedestrians is considered, the green time at intersection m can be extended by 4.68 s. The bus delay increases by

1%, while delays of social vehicles and pedestrians are reduced by 30% and 29% respectively.

7. Conclusion

Based on the previous analysis, we make following conclusions.

(1) A case study is performed using the green phase extension method as an example. The numerical results confirm the effectiveness of the proposed method. This method could reduce the delay of pedestrians significantly without increasing the delay of bus passengers and social vehicle users.

(2) The study only uses the green phase as an example for demonstration. In the future, all combinations of various priority control strategies can be further studied. In addition, this paper only focuses on the two adjacent intersections. In the future, focus can be placed on multiple adjacent intersections or intersections in a region.

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 there is no conflict of interests regarding the publication of this paper.

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