A Signal Timing Model for Improving Traffic Condition Based on Active Priority Control Strategy

Xinyu Tian, Fang Ruan, Hebin Cheng and Qinghe Zheng

Abstract—**By optimizing the signal timing scheme of urban intersection, the implementation of bus signal priority control is undoubtedly to improve the operation efficiency of urban public transport without rebuilding roads and increasing the number of public transport vehicles. However, the accurate detection of the position information of urban public transport vehicles is one of the important reasons that the bus signal priority control system is difficult to be applied to practical projects. In this paper, we propose the signal timing model based on active priority control strategy to improve traffic conditions. The introduction of delay condition, load rate condition, and utility condition can help the model to find the global optimal solution and generalize to the unseen complicated traffic situations. Taking the two-way four-lane intersection as an example, the average travel time, parking times, delay of the social vehicle, and the public transport vehicles at complicated intersection are comprehensively analyzed through simulation and experiments. Finally, the experimental results show that the machine model can automatically determine the optimal location of triggering area of bus signal priority at a two-way four-lane intersection. Compared with different approaches, our proposed model can achieve the state-of-the-art performance.**

Index Terms—**signal timing model; active priority control; traffic condition; global optimal solution**

I. Introduction

By optimizing the signal timing scheme of intersections in the city, the implementation of bus signal priority control can undoubtedly improve the operation efficiency of urban public transport without rebuilding roads and increasing the number of public transport vehicles. However, the accurate detection of the position information of urban public transport vehicles is one of the important reasons that the bus signal priority control system is difficult to be applied to practical projects [1]. In the past, the bus signal priority detection system was mainly based on the induction coil [2], optics [3], acoustic wave [4], radio frequency [5], and GPS positioning system [6], etc. When the detection system determines the specific area where the bus vehicle enters the intersection, that is, the transit signal priority traffic trigger area, the priority pass request will be sent to the signal control center immediately.

Since 1970, bus lanes (roads) have been widely accepted as a means of bus priority to solve the increasing traffic demand and traffic delays. The research on priority traffic technology of urban public transportation in our country started relatively late. So far, most of the researches and explorations on traffic optimization of the public transportation is basically in the theoretical stage, and the specific application of priority traffic technique has not been much involved. Bus priority technology includes the realization of bus priority in space and time access rights. Spatial priority can be achieved by setting up bus lanes (roads) or some sawtooth bus priority entry lanes. In fact, the time priority means signal priority, and thus advanced communication and information technology, control technology, and computer technology can be used. Through intelligent signal controllers [42] [43] [44], the bus priority intelligent control strategy can be then applied to the various operation process. We summarize the advantages and disadvantages of various techniques, as shown in Table I.

It is worth noting that the circuit design of traffic signal controller includes synchronous circuit, asynchronous circuit and random circuit, etc. The hardware structures of the signal controller are also described in a variety of ways, including behavior description [45], register transfer description [46], and structure description. The emergence and development of various design methods and hardware description techniques make the traffic signal control design convenient and easy to employ. However, the shortage of unified standards makes it difficult for different designing procedures and description languages to interoperate, which is not conducive to the long-term development of traffic signal controllers [14].

At present, a large number of related technologies [7] have been developed to optimize traffic, including route navigation, vehicle flow control, signal planning. Ma *et al.* [8] proposed a theoretical model of the relationship between the location of the bus priority detector and the bus signal priority system. Cao *et al.* [9] established a mathematical model based on waiting time of bus at crossing to determine the location of the detector. Ma *et al.* [10] established a machine model with the minimum delay of bus traffic at the intersection to determine the priority location of the bus signal. Zeng *et al.* [11] studied and analyzed the influence of bus countdown signal on the

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TABLE I
ADVANTAGES AND DISADVANTAGES OF VARIOUS TECHNIQUES

Performance	Induction coil	Infrared ray	GPS	Video	RFID
Advantages	simple and reliable	simple and accurate	intuitive and accurate	intuitive and accurate	unaffected by environment
Disadvantages	excavating the road and not classifying various vehicles	distance is affected by the environment and not robust	low precision and high price	easily affected by the environment and costly	labels need to be installed on the car.

implementation efficiency of active priority control strategy, and then proposed optimal position and solution of detector arrangement.

In this paper, we propose a signal timing model based on active priority control strategy to improve traffic conditions. The introduction of delay condition, load rate condition, and utility condition can help the model to find the global optimal solution and generalize to the complicated traffic situations. Taking the two-way four-lane intersection as an example, the average travel time, parking times, delay of the social vehicle, and the public vehicle at the intersection are comprehensively analyzed by simulation. Finally, the experimental results show that machine model can automatically determine the optimal location of triggering area of the bus signal priority at a two-way four-lane intersection. Compared with various methods, our proposed signal timing model can achieve the state-of-the-art performance.

The structure of paper is organized as follows. In Section II, we give a brief review on the signal timing scheme for improving traffic condition. In Section III, we introduce the signal timing model based on active priority control strategy. In Section IV, experimental results are shown to illustrate that the model can automatically determine the optimal location of triggering area of bus signal priority at a two-way four-lane intersection. Finally, we conclude the paper and points out the further work in Section VI.

II. RELATED WORK

In practical applications, the requirements of signal timing scheme of traffic lights are more complicated than those in the simulation cases [38] [39] [47] [48] [49], and the following conditions are usually required:

- The setting of signal lights should be coordinated with the information expressed by traffic signs, markings and other facilities, and should not be self-contradictory.
- The combination of signal lights should be coordinated with the division of guiding lanes, and the lights of the direction indicator should be selected reasonably.
- The green time should ensure that pedestrians can walk across the street safely. Signal release rules should be basically the same on a road within a city.
- The signals of main and secondary main road junctions should be coordinated and optimized, respectively. The coordinated control and optimization of the first and secondary trunk signal junctions

To meet these practical needs, a large number of algorithms have been proposed and studied. Tong *et al.* [29] proposed a stochastic programming model for oversaturated intersection and showed this new model can give a better performance in total vehicle delay and throughput. Li *et al.* [30] proposed a set of methods to improve signal timing schemes via deep reinforcement learning. Jang *et al.* [31] developed a signal optimization method that aimed to equalize queue growth rates across links in oversaturated urban roadway networks and thus postponed the queue spillbacks that form at the localized sections of networks. Agbelie *et al* [32] investigated the impacts of signal-related, traffic, and highway geometric features on the crash frequency at complex urban signalized intersections. Osorio *et al.* [33] proposed a methodology that allowed high-resolution traffic and emissions models, known as microscopic simulation models, which can be efficiently used to address the transportation optimization problems that accounted for complex environmental metrics. Papatzikou *et al.* [34] proposed an optimization algorithm through combing the dynamic traffic assignment and network control, whose objective is to minimize the potential risk of travel time loss. Chen *et al.* [35] proposed an improved adaptive control method by combining a vehicle arrival estimation model with a signal optimization technique. Teman *et al.* [36] designed a methodology which introduced controlled placement, leading to a structured and non-congested layout with close to 100% placement utilization. Mannion *et al.* [37] described an deep learning based autonomic method for adaptive timing signal control.

III. SIGNAL TIMING MODEL BASED ON ACTIVE PRIORITY CONTROL STRATEGY

A. Triggering Area of Bus Signal Priority

The bus lane near the intersection is divided into three parts: the driving area, the lane buffer zone, and the priority traffic trigger area, as shown in Fig. 1. When the bus signal priority detection system detects the bus priority driving trigger area, the bus vehicle priority access request is triggered and sent to the signal control center to make a priority pass decision [13].

When the system detects the arrival of the BRT vehicle, it immediately executes the priority signal strategy and takes the corresponding action to control the light [20] [21]. However, considering the signal switching phase time t_1 and the driver need to see the signal indication time t_2 ahead of time, the vehicle detection positions should not be placed at the intersection, but should be detected ahead of time. It can be seen from Fig. 1 that the BRT vehicle has a distance from detected position to the intersection, and if the BRT vehicle is planning to pass the traffic light of the intersection smoothly, the system needs to reserve time $T \geq t_1 + t_2$ for the BRT vehicle. According to the experience value, it can be set to 10s-15s, assuming that the BRT vehicle passes through the intersection at a speed of 20km/h, then the distance $S =$

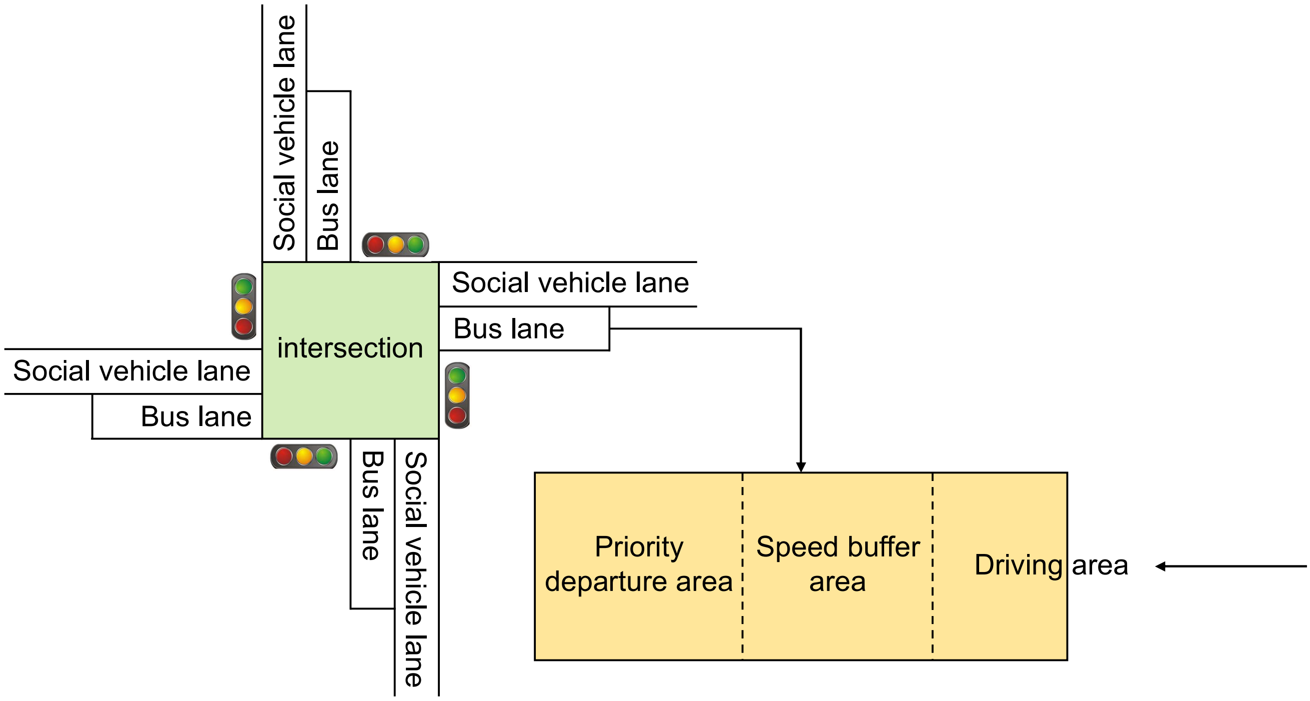


Fig. 1. The bus lane near the intersection that includes three parts: the driving area, the lane buffer zone, and the priority traffic trigger area.

55m-83m. If we want to guarantee the BRT vehicle to pass through the road at a speed of 40 km/h, then the distance S can be set to 110m-166m. Therefore, the distance between vehicle detection position and intersection can be set to between 80m and 150m, according to the actual traffic conditions and road capacity [12] [18] [19] [24] [25] [40] [41] [50].

B. Bus Signal Priority Control Rule

To implement the bus signal priority control strategy at the urban intersection, it is necessary to establish the bus signal priority rules and give priority to the public transport vehicles in the direction that meets the conditions, so as to balance the vehicle delay and the per capita delay in each direction of the intersection.

Considering the overall traffic efficiency of intersections, the priority rules of bus priority requests can select the delay conditions, the passenger loading rate conditions, the utility conditions, and control conditions as the limiting conditions [15]-[17].

Delay condition. To ensure the punctuality of bus arrival time is one of the important factors to improve the service level of public transport vehicles. Therefore, the delay time of public transport vehicles should be considered first when the bus priority control rules are set. The longer the delay is, the higher the priority given to the bus will be, *i.e.*,

$$T' - T > T_{max} \tag{1}$$

where T' is the predicted arrival time of the BRT vehicle, T represents the arrival time of the bus arrival schedule, and T_{max} denotes the maximum acceptable delay time for the bus control system.

When the bus arrival time T' and the arrival time T of the bus arrival schedule exceed the maximum delay time T_{max} that can be tolerated by the bus control system, that is, satisfying the Equation (1). In order to shorten the travel time and waiting time of the bus passengers and improve the bus service level, priority should be given to the public transport vehicle.

Passenger rate condition. The vehicle full load ratio is the ratio between the number of passengers and the capacity of the public transport vehicle. When the bus vehicle is delayed, the per capita delay caused by the high full load rate bus vehicle is relatively high. Therefore, the higher the full capacity of the bus is, the higher the priority will be, *i.e.*,

$$\frac{p}{c_{max}} > R_{min} \tag{2}$$

where p denotes the actual carrying capacity of public transport vehicles, c_{max} is the maximum capacity of the public transport vehicles, and R_{min} is the lower limit of passenger carrying rate of priority public transport vehicles.

When the actual carrying rate of public transport vehicles exceeds the lower limit R_{min} of the priority bus vehicle, that is, the Equation (2), we may consider giving priority to the public transport vehicle whose passenger rate is not lower than this threshold. It can be used to reduce the per capita travel time of public transport travelers, and embody the concept of public transport people-oriented.

Utility condition. The main purpose of implementing bus signal priority is to alleviate the current situations of urban traffic congestion and to improve the efficiency of the whole traffic system. When the positive utility of bus priority control (the total delay of decrease in the number of public transport vehicles and social vehicles in coordinated phase) is greater than that of the negative utility (the total delay of the increase in the number of public transport vehicles and social vehicles in the non-coordinated phase), consideration may be given to giving priority to the bus, *i.e.*,

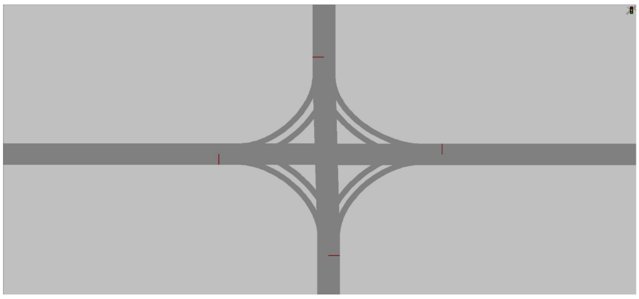


Fig. 2. The simulated entrance lanes.

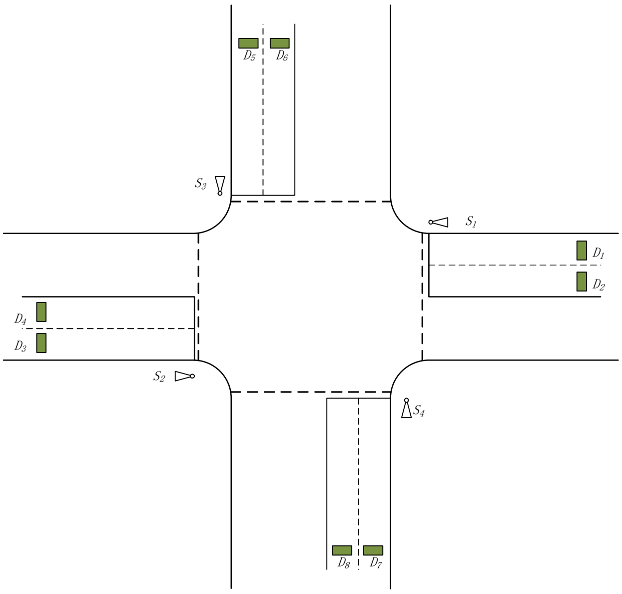


Fig. 3. The layout of signal lights and BRT bus vehicle detectors at two-way four-lane intersections.

$$f_b - f_s > 0 \tag{3}$$

where f_b is the positive utility of bus priority control, and f_s is the negative utility of bus priority control.

If the per capita total delay is used to calculate the utility, the bus priority control will be used, and the delay of the bus and the same social vehicle will be reduced as the following:

$$f_b = r\sum_k \sum_j \left[d_{ijk,G_p}\left(c_{ijk} + W_{ijk}\right) + Bd_{sij,G_p} G_{ep} \right] \tag{4}$$

where r is the waiting time of bus priority, G_p is the sum of green time and yellow light time, G_{ep} represents the effective green light time, W_{ijk} is the social impact value coefficient of delayed bus. d_{ijk,G_p} ($d_{ijk,G_p} = 1$ or $d_{ijk,G_p} = 0$) indicates whether the bus leaves in G_p time, which is the departure rate of social vehicles in G_p time period, and B denotes the average number of passengers carried by social vehicles.

Then the negative utility of public transport priority f_s is the increasement of the delay of public transport vehicle and social vehicles with non-priority phase, and the delay of non-priority phase increase of public transport vehicles is as follows:

$$D_1 = \left(C - G_p\right)\sum_{i,j}\sum_k D_{ijkP} C_{ijk} \tag{5}$$

Thus, the delays of increased social vehicles in non-priority phase is

$$D_2 = \left(C - G_p\right) BD_{sijP} \tag{6}$$

Then we can get

$$f_s = D_1 + D_2 \tag{7}$$

where C is a signal period, D_{ijkP} ($D_{ijkP} = 1$ or $D_{ijkP} = 0$) is the number of social vehicles delayed to reduce the green time, and D_{sijP} is used to reduce the green time of non-priority phase.

Priority calculation of the bus signals. The priority calculation model of bus signal is established in this stage, which is used to determine whether to prioritize public transport vehicles with priority traffic request, to adjust the signal timing scheme, and to carry out the bus signal priority control for the signal control center. And then we can calculate the priority of the bus based on the detected information.

According to the real-time operation status of the bus, such as early, late and carrying rate, when the bus enters the bus priority control area, the priority weight of the bus is calculated according to the detected information [22]. The equation is given as follows:

$$\omega_i = P_i \times \left[1 + \varphi\left(d_i\right)\right] \tag{8}$$

$$\varphi\left(d_i\right) = \begin{cases} 0 & d_i < L_{max} \\ k\left(t\right) \times d_i & d_i \geq L_{max} \end{cases} \tag{9}$$

where ω_i represents the priority weight of the bus that applies for priority traffic, P_i is the passenger carrying rate of the bus, $\varphi(d_i)$ is the weight function of the delayed state of the bus. d_i is the deviation value of the bus vehicle compared with the bus arrival schedule, and the delay arrival is positive, while the early arrival is negative. $k(t)$ is the compensation coefficient of the delayed state of the bus at t moment. L_{max} is the maximum acceptable delay time for the bus control system mentioned above. When the actual arrival time of the BRT bus exceeds the maximum acceptable delay time of the control system, the value of the function $\varphi(d_i)$ increases and the priority weight ω_i of the bus increases [23].

Therefore, considering the actual early and late bus and the actual number of passengers, the bus with long delay time and high passenger rate has higher priority at the intersection. However, due to the large traffic volume of public vehicles, it is difficult for the control center to meet the priority traffic request of all the public transportation vehicles. Therefore, the utility condition mentioned in the above part is used as the criterion for judging whether the priority application of the public transportation vehicle is added to the priority control queue. If the positive effect of the bus priority control is

TABLE II
TWO-WAY FOUR-LANE INTERSECTION TRAFFIC FLOW (UNIT: VEHICLE / H)

Name	Traffic flow		
	Import road	Social vehicle	BRT Bus
Two-way four-lane	East	2440	50
	West	3021	60
	North	2980	60
	South	1887	35

TABLE III
SCHEME OF INTERSECTION SIGNAL TIMING AND PHASE (UNIT: S)

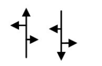
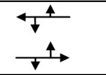
Name	Period length (m)	Phase and its green time (s)	
		Phase 1	Phase 2
Two-way four-lane	130		
		60	60

TABLE IV
SIMULATION RESULTS OF FIXED SIGNAL TIMING SCHEME FOR TWO-WAY FOUR-LANE INTERSECTION

Fixed signal timing scheme		Time/s
Average travel time at intersection	Social vehicles	76.9
	BRT buses	107.7
Average travel time of social vehicles	North entrance	74.9
	South entrance	81.3
	East entrance	68.7
	West entrance	82.5
Average travel time of BRT buses	North entrance	105.6
	South entrance	126.6
	East entrance	86.1
	West entrance	111.4
Number of stops	Social vehicles	1.77
	BRT buses	1.53
Delay time	Social vehicles	45.2
	BRT buses	41.5
	Per capita	44.5

greater than the negative effect, *i.e.*, when the equation (3) is satisfied, the priority request of the bus that requests the priority traffic can be included in the priority control queue, otherwise it will not be considered.

IV. SIMULATION RESULTS AND ANALYSIS

In this section, we introduce the setup of the simulation experiments, the simulation results, and the comparison of the various algorithms, in order to illustrate the effectiveness of our proposed model. The settings and simulation results are shown in part *A* and the rest parts, respectively.

A. Intersection Design and Traffic Flow

According to the actual traffic situation of two-way four-lane intersection in city Jinan of Shandong province, China, it can be seen that the characteristics of early and late rush hours are very obvious, traffic congestions are serious, and although there are many public transport vehicles passing through the intersection, there are still no bus lanes. In this paper, we take the two-way four-lane intersection as the simulation object to set up the experimental simulation road network, and carry out the simulation experiments. The settings of the entrance lanes and the traffic flow of the intersection are shown in Fig. 2 and Table II, respectively.

B. Verification of Signal Timing Scheme at Intersection

The two-way four-lane urban road intersection generally adopts the timing signal timing method, and the signal phase setting only adopts the most traditional signal phase scheme. The specific signal phase scheme and the green time of each phase are shown in Table III. It can be seen that there is a 5s yellow light time after the end of each green light phase.

C. VISVAP Signal Control Implementation

According to the flow and limitation of bus signal priority control mentioned above, the traffic induction signal control based on phase and stage is realized by VISVAP programming. Then, the real-time signal timing scheme is adjusted in the simulation process of bus signal priority control.

Based on the real-time signal timing scheme of bus signal priority control, the layout of signal lights and BRT bus vehicle detectors at two-way four-lane intersections is shown in Fig. 3. S_i (i = 1, 2, 3, 4) denotes the signal lights and D_i (i = 1, 2, …, 8) represents the deployed bus vehicle detectors. In the simulation experiments, the location of the vehicle detector is the location of the trigger area of the bus signal priority. When the BRT bus detector is 1, it means that there is one public transport vehicle passing through. All the two lanes of the entrance road need to be equipped with the bus vehicle detector, since there is no bus lane in the two-way four-lane.

D. Analysis of Simulation Results of Fixed Signal Timing Scheme

We select the three following parameters of social vehicle and bus vehicle delay, average travel time and parking times as the traffic evaluation index. Taking the traffic index of fixed signal timing scheme and real-time signal timing scheme as reference, the influence of setting various traffic signal priority trigger area on traffic evaluation index at two-way four-lane intersection is explored and analyzed. Due to the randomness of simulation process of traffic simulation software VISSIM, the simulation experiments of each scheme are carried out five times, and the average value of the simulation results is taken as the final performance.

As shown in Table IV, the above traffic evaluation index is obtained from the simulation experiment of the two-way four-lane intersection under the fixed signal timing scheme designed in Table II, which is used as the comparative parameters of the subsequent experiments.

E. Analysis of Simulation Results of Real-time Signal Timing Scheme

Average travel time. The travel time is an evaluation of the travel time required by the vehicles on the road from the start of the detection section to the end of the detection section, including the parking waiting time. The travel time of public transport vehicles can be used as one of the most important indicators to evaluate the service level of the public transport system. It effectively reflects the time required for travelers to take public transport vehicles on the road, and has the very important influence on whether travelers choose to take public transport.

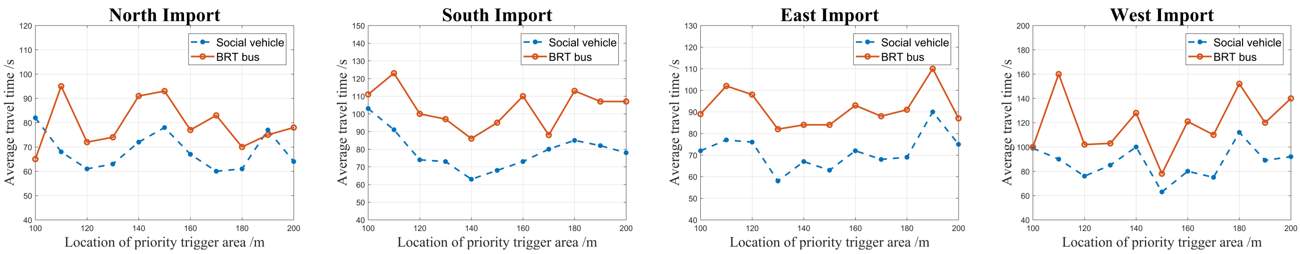
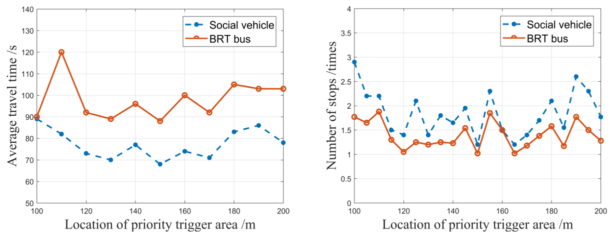


Fig. 4. The average travel time of social vehicles and public transport vehicles in various directions.



(a) (b)

Fig. 5. The average travel time of the social rolling stocks and the public transportation vehicles at intersection are obtained in (a), and the number of parking times of social vehicles and public vehicles at intersections is shown in (b).

We simulated the average travel time of social vehicles and public transport vehicles in twelve directions. According to the proportion of traffic flow in each direction, the average travel time of social vehicles and public transport vehicles imported from north, south, east, and west are calculated. In the scheme of the bus signal priority timing scheme, the length of priority traffic trigger area is set between 100m and 200m. The average travel time of social vehicles and public transport vehicles in various directions is shown in Fig. 4. When the length of the priority traffic trigger area is 170m, the average travel time of social vehicles in the north entrance lanes of the intersection is the shortest, *i.e.*, 61.4s. And compared with the corresponding average travel time under the fixed signal timing scheme, it is reduced by 18%; when the length of priority traffic trigger zone is set to 100m, the average travel time of the bus in the north entrance lane of the intersection is the shortest (*i.e.*, 64.4s), bring a 39% reduction.

Parking times. According to the weight distribution of the traffic flow distribution of each import lane, the average travel time of the social rolling stocks and the public transportation vehicles at intersection are obtained, as shown in Fig. 5a. The average travel time of the passing vehicles at the intersection varies depending on the setting position of the priority pass trigger zone. When the position of the priority traffic trigger zone is set between 130 meters and 170 meters, the average travel time of the social vehicles and the bus vehicles passing through the intersections are improved compared with the relevant parameters under the fixed signal timing scheme. Among them, when the length of priority traffic trigger zone is set to 150m, the average travel time of social vehicles and public transportation vehicles at the intersection reaches the minimum of 69.1s and 88.7s, respectively, which brings the reduction of 10.1% and 17.6%.

Delay. When the priority pass trigger area is set between 100m and 200m, as shown in Fig. 5b. As with the different locations of priority traffic trigger area, the number of parking times of social vehicles and public vehicles at intersections is changed. When the priority traffic trigger areas are located between 120m and 170m from the parking line and 200 meters. The number of stopping times of social vehicles and public transport vehicles at intersections is less than that of the social vehicles and public transport vehicles under the fixed signal timing scheme. And when the trigger area of public priority traffic is set at 150m, the number of parking of social vehicles at intersections is 1.25, and the number of parking of public transport vehicles is 1.02. And compared with the fixed signal timing scheme, the results are reduced by 29.4% and 33.3%, respectively.

Then we present the relationship of average travel time and the location of priority trigger area under various methods, as shown in Fig. 6. It can be seen that the average travel time for both types of vehicles (BRT bus and social vehicles) is between 50-100s and 70-110s, respectively. Furthermore, our proposed method achieves the lowest average travel time of both BRT bus and social vehicles.

On the other hand, the change of the number of BRT bus and social vehicles over time is also shown in Fig. 7. Before 4 hours, the number of vehicles gradually rises and then begins to decline, eventually tending to zero. It is noteworthy that the number of social vehicles has always been lower than that of BRT buses, which may be due to the lack of dedicated access for social vehicles. Reasonable arrangement of the BRT buses and social vehicles can speed up regional traffic.

V. Discussions

In this part, we summarize the advantages of the proposed algorithm and the challenges in practical application. With the rapid increase in the number of urban vehicles of various types in the city, the contradiction between vehicles under the condition of limited road area is becoming more and more prominent, and it is unrealistic to simply increase the road area. Reasonable control of urban traffic lights can improve traffic flow quality and improve transport capacity

The traffic signal timing model based on active priority control strategy has the following advantages:

- The algorithm has high real-time performance and can deal with the change of traffic flow in various situations in time.
- The performance of the algorithm is robust to the change of traffic flow, and can therefore significantly improve the arrangement of vehicles under high traffic flow.
- The proposed algorithm can be generalized in different road environments, such as intersections and T-junctions, etc.

On the other hand, the algorithm still has some limitations in practical application. In the real environment, the signal

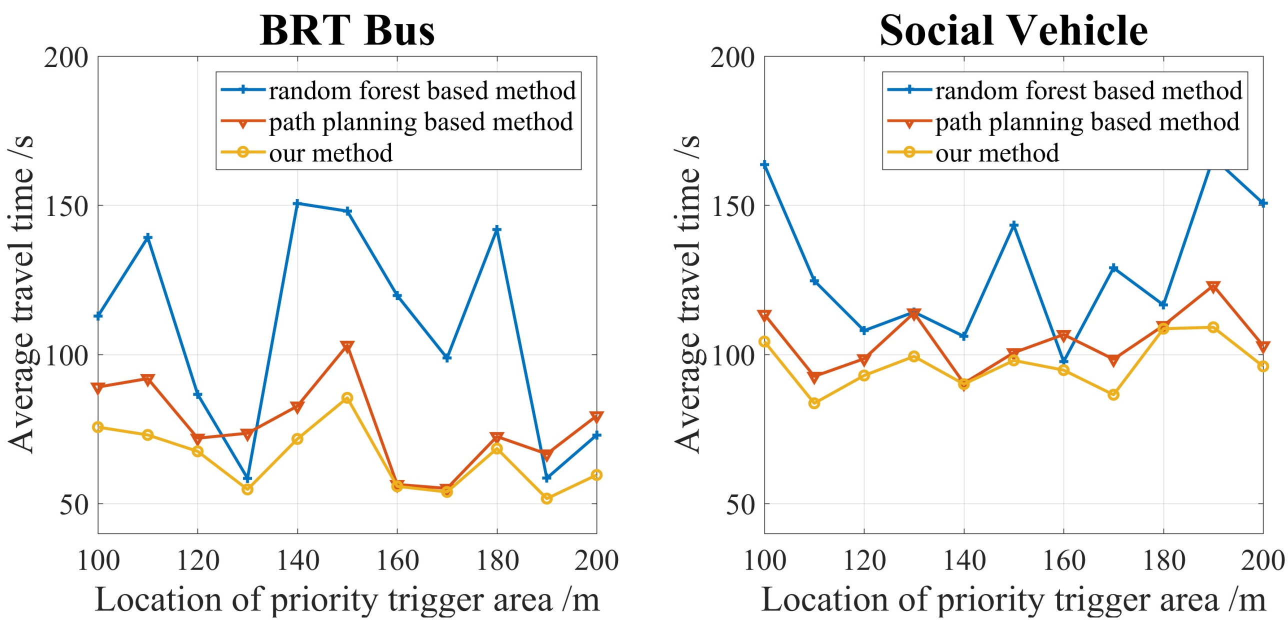


Fig. 6. The relationship of average travel time and the location of priority trigger area under various methods.

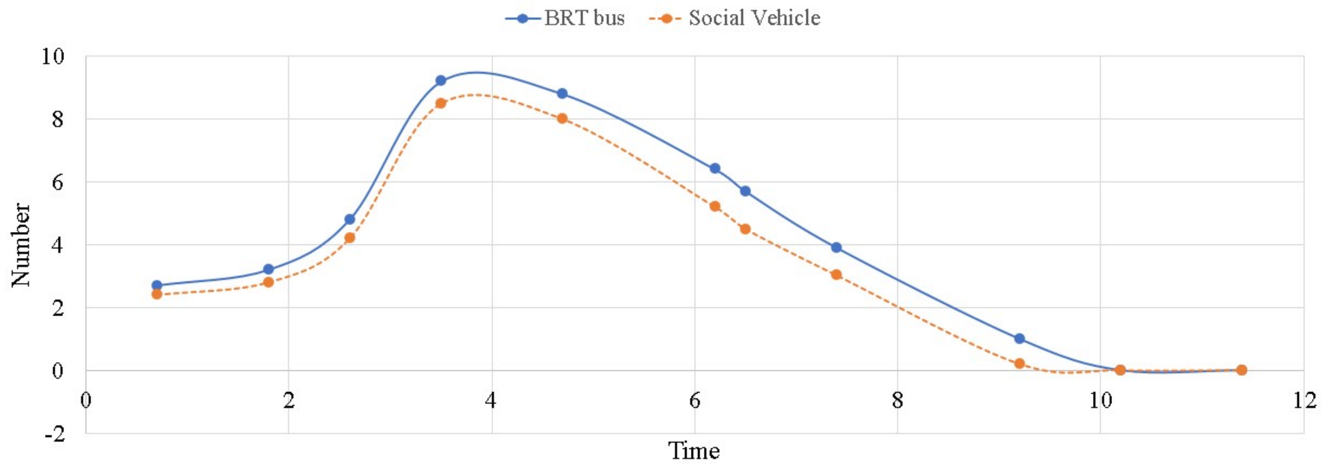


Fig. 7. The change of the number of BRT bus and social vehicles over time.

timing scheme also needs to consider the changes of traffic conditions caused by complex weather and special events. Moreover, it is difficult to accurately and reasonably evaluate the performance of the signal timing scheme in practical application, which is another obstacle hinders its application in the real environment.

VI. Conclusion

In this paper, we propose the signal timing model based on the active priority control strategy to improve the traffic conditions. The introduction of delay condition, load rate condition, and utility conditions can help the model to find the global optimal solution and generalize to unseen complicated traffic situations. Taking the two-way four-lane intersection as an example, the average travel time, parking times, delay of the social vehicle, and the public transport vehicle at the intersection is explored and analyzed by extensive simulation and experiments. Finally, experimental results show that the model can automatically determine the optimal location of triggering areas of the bus signal priority at the two-way four-lane intersection. Compared with various methods, our proposed model can achieve the state-of-the-art performance, *i.e.*, the average travel time, the number of stops and the delay of social vehicles are reduced by 10.1%, 29.4%, and 30.3%, respectively. Moreover, the average travel time, the number of stops, and the delay of the bus decreased by 17.6%, 33.3%, and 26.7%, respectively. It can be seen that our proposed method shows a great advantage by comparing with other advanced methods.

In the future, we plan to validate the effectiveness and reliability of the traffic light signal timing scheme in more complex road conditions, such as multi-vehicle road junctions and high-traffic intersections that are easy to block.

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