RESEARCH ON TRANSIT SIGNAL PRIORITY CONTROL STRATEGY BASED ON REAL-TIME SATURATION DETECTION FOR A SINGLE INTERSECTION [1]

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1. Introduction

The concept of bus priority is an important way to promote the development of urban public transport and reduce traffic congestion. However, bus signal priority is an effective way to reduce bus travel time, reduce vehicle delay and improve the efficiency of public traffic. Therefore, the research on the theory of transit signal priority control in urban road intersection is of great significance for promoting the development of urban public transportation and realizing the efficient operation of the urban traffic system.

Many scholars both at home and abroad have made a great deal of researches on transit signal priority, the transit signal priority strategy develops from absolute signal priority strategy to finite signal priority strategy. Ludwick (1976) put forward the unconditional priority strategy can make bus travel time by 25%, but the delay of social vehicles on the other road increase. Vincent(1978) proposed five strategies, (1) only green light extension, (2) green light extension and early break of red light with green-time compensation, (3) green light extension and early break of red light considered without green-time compensation, (4) only early break of red light with green-time compensation, (5) only early break of red light without green-time compensation, the result shows that the single control strategy can't improve the traffic efficiency obviously, but the combined strategies can greatly improve the transit efficiency. Elias and Wilbur(1976) proposed a bus priority control strategy considering the arrival of transit based on bus departure timetable, the control strategy can effectively reduce the delay time of transit and the travel time is reduced by 23%. Zou Z(2008) takes Paris Champs Elysees street as an example, and proposes a real-time traffic signal priority control algorithm based on real-time detection. The algorithm defines three consecutive stages which are called the stage of initial selection, the stage of feasibility study and the stage of priority implementation. The method can improve the efficiency of transit by using the strategy of the green light extension, the strategy of early green and the strategy of green light restarts.

At present, the priority signal control strategy of transit is aimed to improve the efficiency of bus transit as a target, and they take little account of the effect on social vehicles. YM Bie(2011), in order to reduce the influence of bus signal priority on the social vehicles, a finite signal priority strategy considered saturation constraint is proposed and simulated by VISSIM simulation. D Qiu(2014), the method of calculating the congestion rate based on the critical queuing length is proposed. Based on this, a priority traffic control strategy for single intersection is designed based on the value of congestion rate. The experimental results show that the method can effectively alleviate the congestion of non-priority vehicles while improving the traffic efficiency of buses. However, existing research is implemented by adjusting the critical green light time in real time. Historical analysis data are used as the method for judging the green light time in the subsequent period. The real-time performance is poor, and the response of the bus signal priority strategy has a certain lag.

Therefore, this paper calculates the green light time based on the shortest cycle duration and the best cycle duration, so as to determine the range of compressible green light time. Based on the critical

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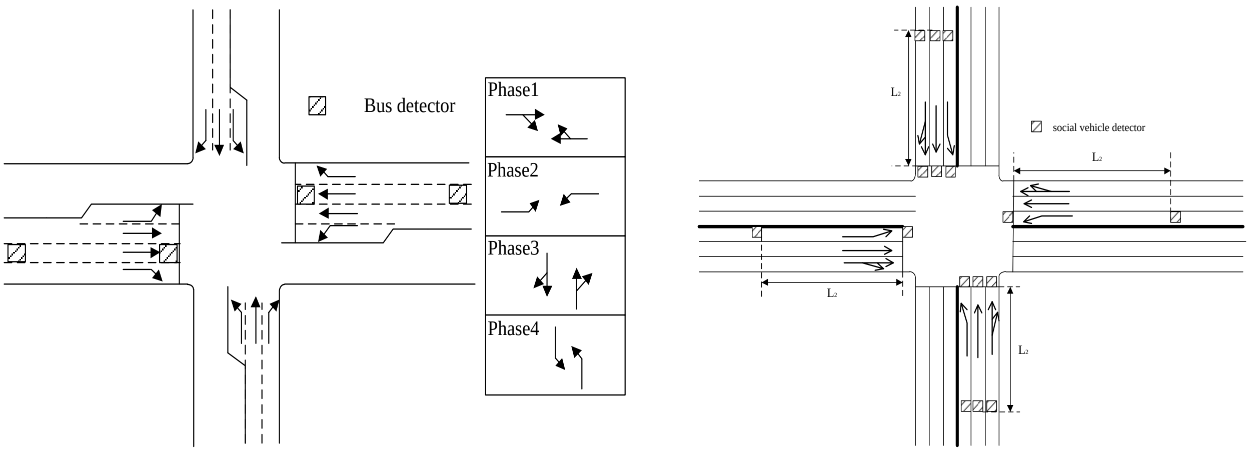
saturation constraints, we formulated conditional response to bus signal priority control strategy, green light extension strategy, red light early break strategy, and combined strategy.

2. The layout of the detector

2.1 Layout of the bus detector

For the study of single-point bus priority signal control, we only discuss the control design under single-phase bus priority condition. Based on the layout method of detectors provided by YM Bie(2011), we put the detectors on the stop line of the intersection and the place 80-meter off the stop line as the figure 1(a) shows. The bus priority phase is the straight phase from the east-west enter line, and there is no bus lane on the other enter line, where the signal only responds to the priority requests from the east-west straight direction buses.



(a) Bus detector layout (b) Layout of vehicle detector for non-priority phase

Figure 1 Layout of the detector

2.2 Layout of the social vehicle detector

Based on the setting method of deceleration section and length of storage section provided by no.7 reference and the standard for queuing length of service level given by traffic engineering, we put the vehicle detectors 120 meters in front and at the back of the stop line. Non bus signal priority phase vehicle detector setting position shown in Figure 1(b). During the red light period, vehicles stop at the stop line on the cross, and later arriving vehicles start queuing. The detectors determine the queue length of non-bus priority direction by real-time detection of the number of vehicles in the interval. Besides, this method can also be used to detect the traffic volume of the social vehicles which reach during the period of time, and can also be used to detect the dissipated and residual social vehicle flow during the detection period.

3. Models

3.1 Priority strategy response

The single-intersection bus signal priority control strategy proposed in this paper takes the fixed period duration as the limiting condition, taking into account the influence of social vehicles for non-priority phase. In this paper, the non-priority phase intersection saturation is defined as the condition, and the saturation of the non-priority phase at the end of each cycle is calculated in real time to determine whether the next cycle is to provide bus signal priority service for the priority phase. Saturation detection module control algorithm process is shown in Figure 2.

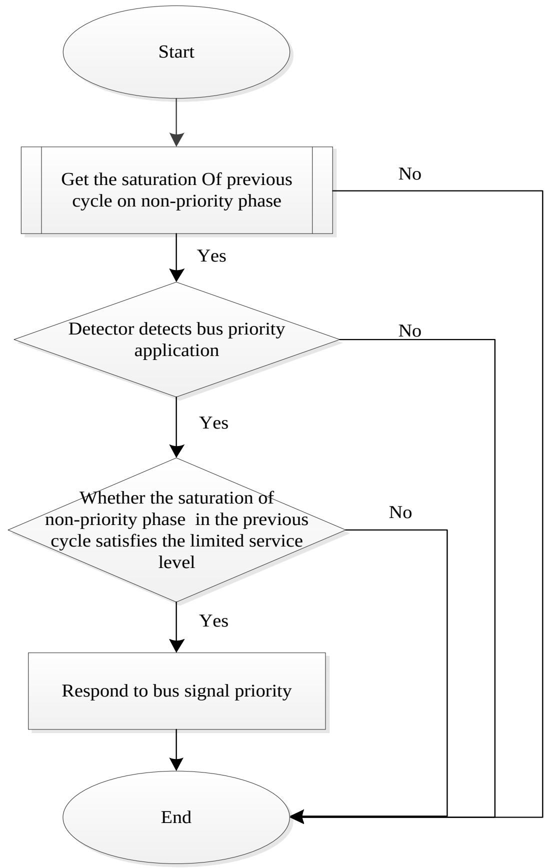


Figure 2 Saturation detection module flow chart

Due to the fixed duration of the design scheme, because of the priority of the bus signal, the actual green time of each non-priority phase will change and the actual green time will also change. The saturation of non-priority phase at the end of the signal period is calculated as follows:

$$x_{jp} = \frac{q_{jreal} \cdot (\sum_{j}^{n} g_{jreal} + g_{ireal})}{S_j \cdot g_{jreal}} \tag{1}$$

Where

x_{jp} is the saturation of non-priority phase *j*,

q_{jreal} is the number of vehicles arriving in this cycle for non-priority phase *j* in critical lanes,

g_{jreal} greal is the actual green time of this cycle for non-priority phase *j*,

g_{ireal} is the actual green time of this cycle for priority phase *i*,

S_j is the Saturated flow rate in critical lanes for phase *j*.

3.2 Timing scheme design

Bus priority time needs to compress the green time of non-priority phase. Therefore, prior to developing bus priority strategy, we must first determine the green time threshold of non-priority phase. This article distributes the minimum green time and maximum green time for each phase based on the minimum and optimal cycle duration.

(1) Minimum cycle duration

The duration of the shortest period can completely evacuate the vehicles that arrive within one cycle. No green time is left in the period. The formula for the shortest period length is as follows:

$$C_{\min} = \frac{L}{1-\sum_{i=1}^{n}\frac{q_i}{S_i}} = \frac{L}{1-\sum_{i=1}^{n} y_i} = \frac{L}{1-Y} \tag{2}$$

Where

q_i is the traffic flow volume in key lanes for phase *i*(pcu/h),

S_i is the saturation flow rate in key lanes for phase *i*(pcu/h),

y_i is the phase saturation for phase *i*,

Y is the sum of phase saturation.

(2) Optimal cycle duration

There is no extra green time during the shortest period of time, and the arrival of traffic has obvious randomness. Therefore, it is necessary to set a certain amount of green time and increase the capacity of the intersection. This paper uses the TRRL method (Webster timing method) that is widely used internationally to calculate the optimal cycle duration. The calculation formula is described as follows:

$$C_0 = \frac{1.5L+5}{1-Y} \tag{3}$$

The calculation result of the optimal cycle duration is larger than the minimum cycle time, that is, the optimal cycle time will have a part of the green time surplus. This part of the green time can be used as the prior condition for responding to the bus signal priority, and the range of intersection signal cycle length is between the minimum cycle time $C_{\min}$ and the optimal cycle time C_0.

(3) Green time distribution

Phase green time allocation is based on the principle of equal saturation. Minimum phase of green time and maximum green time are calculated by the equal saturation principle from minimum cycle duration and optimal cycle duration respectively.

$$g_{\min}^{i} = \frac{y_i}{Y}(C_{\min}-L) \tag{4}$$

$$g_{\max}^{i} = \frac{y_i}{Y}(C_0-L) \tag{5}$$

Where

$g_{\min}^{i}$ is the minimum green time required for phase *i*,

$g_{\max}^{i}$ is the maximum green time for phase *i*.

3.3 Green light extension strategy

If the bus speed is v_b and the distance from the detector to the intersection is l_b, then the time difference Δt between the detector detecting the priority application and the arrival of the bus at the parking line is l_b/v_b+t_s. The green light extension strategy needs to determine the extendable length of time first, predict whether the arrival of the bus by the real-time detected vehicle arrival information meets the present bus signal priority conditions, and then respond to the limited green light extension strategy. The key steps for the green light extension strategy are as follows:

(1) Calculate the maximum green time that the priority phase can be extended

The maximum time that bus priority phase green light can be extended is the sum of non-priority phase compressible green light time.

$$t_{gext\max} = \sum_{i=1}^{j-1}\left(g_{\max}^{i} - g_{\min}^{i}\right) \tag{6}$$

(2) Calculate the priority phase actual green time

The actual green time of bus priority phase is the sum of base green time and extended green time

$$g_{real} = g_{basic} + g_{extend} \tag{7}$$

Where

g_{real} is the actual green time for bus phase(s),

g_{basic} is the phase base green time(s),

g_{extend} is the green time needed to be extended for bus(s).

(3) Calculate non-priority phase green time

Practice has proved that too small and too long cycle time is not conducive to the passing of vehicles at the intersection. If the upper limit of the cycle is not limited, the frequent arrival of the public traffic will greatly increase the signal cycle of the intersection, thus reducing the overall traffic efficiency of signalized intersection. Therefore, this paper regards the optimal cycle time as the upper limit of the signal cycle of the intersection, and redistributes the green time of the non-priority phase according to the principle of equal flow ratio distribution, so as to effectively ensure that the signal cycle time of the intersection does not change.

$$g_{creal}^{i} = g_{c}^{i} - g_{ext} \cdot \frac{g_{c}^{i}}{\sum_{i}^{j-1} g_{c}^{i}} \tag{8}$$

Where

g_{creal}^{i} is the actual green time of non-priority phase(s),

g_{c}^{i} is the basic green time of the non-priority phase calculated from the optimal signal period(s).

3.4 Red light early break strategy

The key parameters of the red light early break strategy are as follows:

(1) Calculate the maximum time for red light to break early

The maximum value of the priority phase red light early breakage time is the sum of the non-priority phase-rich green light time.

$$t_{rb\max} = \sum_{i=1}^{j-1}\left(g_{\max}^{i} - g_{\min}^{i}\right) \tag{9}$$

(2) Calculate the actual red light early break time

In order to reduce the waiting time of the bus arriving at the intersection during the red light, a segmented red light strategy is adopted, as shown in Figure.3.

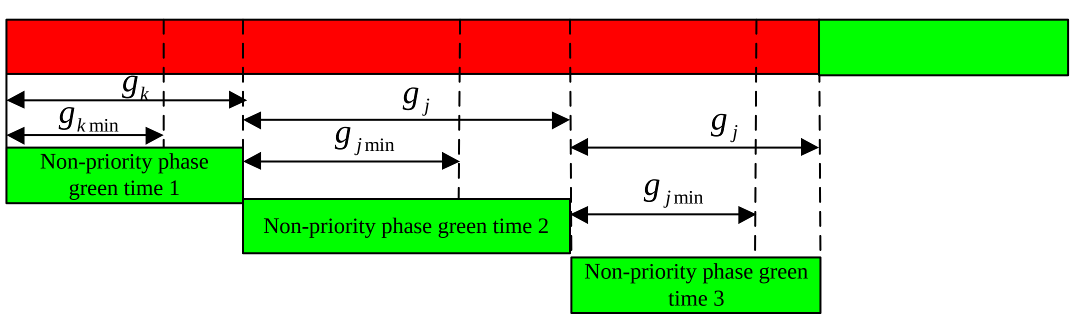


Figure 3 Red light early breaking strategy period division

When the bus arrives at the intersection stop line at the green time of phase *k*, if the current running green time g_{ka} is smaller than the minimum green time g_{km} for phase *k*, the phase signal will be switched to the next phase when the minimum green time g_{km} is reached. If the current running green time g_{ka} is smaller than the minimum green time g_{km} for phase *k*, then it is immediately switched to the next phase. The formula is expressed as follows:

$$g_{kr}=\begin{cases} g_k-g_{k\min}, g_{ka}\le g_{k\min} \\ g_k-g_{ka}, g_{ka}>g_{k\min} \end{cases} \tag{10}$$

If phase j exists between the phase *k* and the priority phase *i* of the next cycle, the maximum red light early breaking time calculated as follows:

$$t_{rb}=g_{kr}+\sum_j g_{jr} \tag{11}$$

(3) Calculate the green light time of non-priority phase in the next cycle

Since the cycle duration set in this paper is a fixed cycle with a limit of the optimal cycle duration, the red light early break time of the current cycle is calculated according to step (2), and the total duration of the double cycle is unchanged as the set condition, then the next period of non-priority phase green time is calculated as follows:

$$g_{ni}=g_{\max}^{i}+g_{kr} \tag{12}$$

4. Case analysis

4.1 Case background

The case intersection is formed by the intersection of two intersecting main roads. The survey period is the late peak (17:30 to 18:30). The east-west traffic is relatively large and the north-south traffic is relatively small. The bus flow of the bus entrance on the west entrance road is 32veh/h, and the bus flow on the bus lane of the east entrance road is 26veh/h.

Traffic flow statistics at various intersections are shown in Table 1.

Table 1 Investigation traffic statistics

The approach	**Left (pcu/h)**	**Straight (pcu/h)**	**Right (pcu/h)**
West	224	1516	265
East	160	1132	183
North	149	1237	164
South	175	909	156

The case intersection original timing scheme uses four-phase fixed signal timing. The phase sequence was east-west straight, east-west-left, north-south straight, and north-south turn left. Based on the measured traffic flow, the signalized intersection timing plan was adjusted. The optimal cycle time was 151s. The green time of each phase is shown in Figure 4.

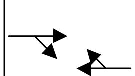
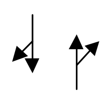
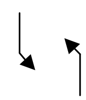
Phase	Phase1	Phase2	Phase3	Phase4
Sequence				
Length	59	25	47	20

Figure 4 signal timing plan

Compared with the non-priority signal scheme, four schemes are designed for comparison. They are only single green light extension strategy considered saturation constraints, only red light early breakage strategy considered saturation constraints, the combined strategy considered saturation constraints, and the combined strategy without considering saturation constraints.

The four comparison schemes are shown in Table 2.

Table 2 Bus priority signal control scheme at single intersection

Number	Signal priority method
Scheme 1	Only single green light extension strategy
Scheme 2	Only red light early breakage strategy
Scheme 3	The combined strategy considered saturation constraints
Scheme 4	The combined strategy without considering saturation constraints

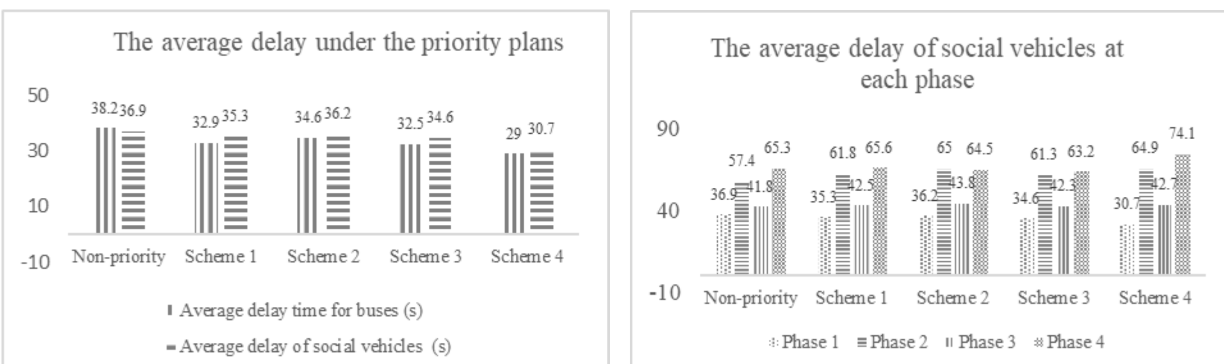
4.2 Evaluation of simulation results

This paper uses VISSIM software to simulate the design logic by calling the VAP module and set the critical saturation to 0.95. The average delay time is used as the evaluation index of the scheme comparison. Statistics on the average delays between public transport vehicles and social vehicles for each program were collected. The statistical results are shown in Table 3.

Figure 5(a) shows the trend of the average delay of public transport vehicles and the average delay of social vehicles under the priority plans. The average delay of social vehicles in non-priority directions at each phase is shown in Figure 5(b).

Table 3 Statistics of vehicle average delays under different control plans

Scheme	Phase 1		Phase 2	Phase 3	Phase 4
	Average delay time for buses (s)	Average delay of social vehicles (s)	Average delay of social vehicles (s)		
Non-priority	38.2	36.9	57.4	41.8	65.3
Scheme 1	32.9	35.3	61.8	42.5	65.6
Scheme 2	34.6	36.2	65.0	43.8	64.5
Scheme 3	32.5	34.6	61.3	42.3	63.2
Scheme 4	29.0	30.7	64.9	42.7	74.1



(a) The average delay under the priority plans (b) The average delay of social vehicles

Figure 5 The average delay of buses and social vehicles

From the data obtained in Table 3, it can be seen that after using the bus signal priority control strategy, the average delay time of public transportation vehicles has decreased, and the average delay time of non-priority phase social vehicles has increased. Compared with the non-priority scheme, the average delay time of public transport vehicles decreased by 13.9%, 9.4%, 14.9%, and 24.0%, respectively.

It can be seen from the trend chart of the average delay changes that the average delay time of bus vehicles in the priority direction has fallen by a large margin, and that of the non-priority direction of social vehicle vehicles has increased slowly. Therefore, the priority signal control method based on green time threshold proposed in this paper effectively improves the service level of public transport vehicles and effectively reduces the time loss of social vehicles.

Compared with Scenario 4, the priority control strategy of public transport signals without considering the service level constraints can more effectively improve the efficiency of the bus and reduce the delay time. The average delay of public transport vehicles decreased by 10.7%. However, the average delays of social vehicles in non-priority phases all increased by 5.8%, 0.9%, and 17.2% respectively. Although Scenario 4 can further reduce the average delay time of public transport vehicles, compared with the impact on social vehicles, the signal priority strategy considering the service level restrictions can make the control system as a whole optimized.

5. Conclusion

Through the real-time inspection of critical saturation, we have conditionally responded to the priority control strategy of public transport signals. This article has formulated the green light extension strategy, the red light early breakage strategy, and the combined strategy. The main conclusions are as follows.

The control strategy proposed in this paper can improve the traffic efficiency of public transportation vehicles. Compared with the non-priority control strategy, only the green light extension strategy reduced the average bus delay time by 13.9%. Only red light early break strategy reduced the average bus delay time by 9.4%. The combined strategy reduced the average bus delay time by 14.9%. In the single strategy formulated in this paper, the green light extension strategy is more efficient than the red light early break strategy in improving the traffic efficiency at the intersection of public traffic vehicles. In the design case of this article, the green light extension strategy is compared with the red light early breakage strategy, which reduces the average delay time of the bus by 4.9%. Compared with the single-signal priority strategy, the combined strategy can minimize the delay time at the intersection of public transport vehicles. Compared with the single green light extension strategy, the combined strategy has reduced the average delay time of buses by 1.2%. Compared with the single red-light early-breaking strategy, the average delay time of public transport vehicles has decreased by 6.1%. Compared with the bus signal priority strategy without considering the saturation constraints, although the average delay time of the bus has increased, the delay time of social vehicles has decreased.

In this paper, the test only validates the peak period of the case, and does not simulate a variety of scenarios to analyze the adaptability of the proposed strategy, and the service level setting is based on the near unstable flow state as the service level limiting condition. We have not analyzed the bus signal priority control strategy under various service levels. In future research, we can adjust the influence factors of signal control by setting environmental variables to carry out sensitivity analysis, and then verify the adaptability of different schemes under different conditions

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