Bus Signal Priority Control Model under Bus Lane

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ABSTRACT. *In order to avoid or reduce the phenomenon of train running in urban public transport, it is considered that when there is a large headway, the control measures of bus speed guidance and bus signal priority should be taken in time to reduce the delay caused by bus stopping and waiting when passing the intersection. Taking the headway of the upstream station of the intersection as the decision index. When the headway greater than 1.5 times of the initial departure interval, implementing the control model. Taking the minimum delay of intersection as the objective, taking the optimization phase and the saturation of influence phase as the constraint conditions, taking the green light adjustment time and cycle length as variables, and considering the change of the travel time due to the speed adjustment to the intersection, a linear programming model of bus signal priority is established. The results show that under the condition of high and low saturation, the headway decreases by 10.3% and 8.0% when the green light is extended, by 0.5% when the red light is cut off early, by 6.1s and 7.0s when the vehicles pass through the intersection, and by 3.1% and 2.7% when the passengers wait for the next station.*

KEYWORDS: *Traffic engineering, Bus signal priority, LP; Bus bunching*

1. Introduction

Bus signal priority can improve the service level of public transport to a certain extent. The implementation of public transport signal priority can reduce the delay of public transport vehicles at intersections caused by the control of signal lights, improve the punctuality rate of public transport, thus improve the reliability of public transport operation, reduce the travel time of passengers, and increase the attractiveness of public transport travel. The processing methods of bus signal priority include passive priority, active priority and real-time adaptive priority control. The change of signal timing will reduce the running time of buses and improve the running condition of traffic flow.

W.J. Ma[1-3] et al. have made in-depth research on the problem of signal priority multiple applications. First, they solve the multi-stage optimal decision-making problem of signal phase sequencing, which can significantly reduce the total delay of priority applications and total vehicle delay. Then, from the perspective of the combination optimization of lane function and signal control, aiming at the social traffic delay and bus delay at intersections, the multi-objective optimization model of passive priority control of public transport at single intersection based on lane is established. Then, considering the environment of vehicle road coordination, combining the speed regulation and signal optimization control, the simulation analysis is carried out with the objective of the optimal operation state of public transport. The results show that public transport can well pass with the maximum possible priority and the optimal speed of energy conservation and emission reduction.

P. Zhang[4] et al. established an integer linear programming model for integrated optimization of speed guidance regulation and signal timing at intersections. Through collaborative optimization of bus speed and signal timing at intersections, the delay and parking times of vehicles at intersections were reduced. The optimization effect was far greater than the traditional first come first service control method and unilateral speed regulation or signal regulation method.

H.L. Dou[5] et al. set the maximum reserve capacity of the total number of passengers passing through the bus and car at the intersection as the goal, constructed the linear programming model of the passive priority of public transport at the single intersection, and the result can guarantee the intersection to obtain greater passenger and vehicle capacity at the same time.

Miquel[6] et al. proposed a dynamic bus control strategy based on the real-time bus tracking data of the station, which combines the speed control of the bus with the signal timing adjustment of the intersection in case of serious delay. The results show that the effect of this control strategy can reduce the operating cost, and the coefficient of change of the headway is significantly reduced.

However, not every bus passing through the intersection needs to provide signal priority service. When the headway is greater than a certain range, the vehicle runs later than the timetable, and the number of passengers waiting at the platform gradually increases with the passage of time, increasing the boarding and disembarking time at the station, and the vehicle dwell time at the station further increases, and then further increases the distance from the front vehicle, and shortens the distance from the rear vehicle. The continuous repetition of this phenomenon eventually leads to the formation of bus queuing operation Train running phenomenon. In order to avoid or reduce the occurrence of the phenomenon, it is necessary to adjust and control the signal of vehicles with excessive headway with the front vehicle, so that they can pass through the intersection as soon as possible and maintain a certain headway.

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2. Public transport signal priority model

2.1 Problem Description and Assumptions

Problem Description: there is a bus lane on the East-West main road. In order to prevent or reduce the occurrence of the bus cross, which leads to the extension of waiting time for more passengers, it is mainly considered to slow down the occurrence of bus queuing through the intersection signal control scheduling method. The bus can reach the intersection through speed adjustment, or adjust the phase length of East-West straight travel, mainly through the intersection by means of green light extension and red light early break. According to the detection, when the headway between the buses of the adjacent shift in the upstream bus station of the intersection is too large, the corresponding scheduling measures are taken to achieve the purpose of reducing the average waiting time of the randomly arrived passengers in the downstream bus station of the intersection.

Hypothesis: (1) the bus runs on the bus lane, and the bus lane is the East-West straight line direction. Only the signal length of one phase of East-West straight line is considered in the priority control.

(2) The detection area is set at the bus platform upstream of the intersection to record the time when the bus arrives at the station.

(3) For passengers at bus stops, the average waiting time of passengers arriving at time interval t is $t/2$, and the number of passengers arriving is directly proportional to the time t, that is μt, the number of passengers, μ is the arrival rate of passengers.

(4) The bus is large enough to accommodate all waiting passengers.

2.2 Constraint Condition

According to Yu[7] for the determination index of the phenomenon of train crossing, that is, when the arrival headway between the front and back buses of the same line is less than 1/4 of the initial headway, this phenomenon is determined as the phenomenon of train crossing. If the headway between a bus arriving at the station and the front car is too large, the headway between the bus and the rear car will be reduced. In addition, the accumulation of road delay, sudden passenger flow and other factors will lead to the phenomenon of train passing. Once such a phenomenon occurs, it is difficult to control two or more vehicles in line. Therefore, in consideration of the situation that the headway is too large, it is necessary to timely prevent the occurrence of train running in advance through the control of intersection signal lights.

In order to leave a certain adjustment space, the signal control is set when the headway of the bus arriving at the station is greater than 3/2 of the initial headway.

$$h_i > \frac{3}{2} h_t \tag{1}$$

The upstream station of the intersection is marked with 1, and the downstream station is marked with 2. The time for bus I to reach the bus station upstream of the intersection is a_{1i}, and the dwell time at the station is d_{1i}. the dwell time d_{1i} is related to the time for passengers to get on and off the bus at the station, $d_{1i} = \max\{B_{1i}, A_{1i}\}$, Generally, it is considered that the boarding time B_{1i} is longer than the boarding time A_{1i}, so $d_{1i} = B_{1i}$, the headway at station 1 is h_{1i}, and the number of passengers at station 1 is $N_{1i} = \mu \cdot h_{1i}$, so the dwell time is $d_{1i} = B_{1i} = \alpha \cdot N_{1i}$, and α refer to the average boarding time of passengers at the station.

The distance from the bus stop at the upstream of the intersection to the stop line at the intersection is L_1, and the average travel time is $\bar{t}_1 = L_1 / \bar{V}$. There is a certain adjustment range Δt_1 according to the adjustment travel time of the vehicle speed. So the time when bus i reaches the stop line at the intersection is

$$S_i = a_{1i} + \alpha \cdot \mu \cdot h_{1i} + \bar{t}_1 + \Delta t_1 \tag{2}$$

The bus lane is only laid in the direction of East-West straight travel, so when considering the optimization of signal timing, adjust the phase of East-West straight travel, and adjust other phases accordingly. The period length of intersection signal is C, the green light time length of optimized phase is g_1, the yellow light interval is e, and the rest is the red light time length r. The start time of the phase green light is g_s, and the end time of the green light is g_d.

When the signal intersection is not optimized, the headway of the front and the next buses arriving at the downstream of the intersection is h_{2i}, and the headway after the signal optimization is $h_{2i}^{'}$. The difference between the headway of the downstream station after regulation and the actual headway only lies in the change of the actual time passing the intersection stop line,

$$h_{2i}^{'} = h_{2i} + \Delta h_i$$

$$\Delta h_i = t_i^{'} - t_i$$

In the formula, t_i represents the time of crossing the stop line without regulation, and $t_i^{'}$ represents the time of crossing the stop line after regulation.

The cycle length of the signal intersection $C = g_1 + e + r$, after the adjustment $C^{'} = g_1 + \Delta g + e + r$, where Δg is the adjustment time of the green light. The bus passing through the intersection is scheduled by the active priority signal control strategy. This strategy contains early stop of the red light and extension of the green

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light. The adjustment time of the green light is recorded as Δg_1 and Δg_2 respectively.

The adjustment of green time is closely related to the vehicle across the whole intersection. In order to reduce the impact of the change of signal phase on the intersection, only the phase duration of the signal cycle for which the public transport priority application is made is changed, and the cycle length does not exceed the upper limit $C_{\max}$.

$$C' = C + \Delta g_1 \quad \text{or} \quad C' = C + \Delta g_2$$

$$C' \le C_{\max}$$

In order to ensure smooth traffic after signal adjustment, the phase saturation shall not exceed $x_{\max}$. The initial green time of the phase affected by the adjustment signal is recorded as g_2, the maximum value of the corresponding phase saturation is $x_{1\max}$, $x_{2\max}$, and the flow ratio is recorded as y_1, y_2.

Figure. 1 (a)

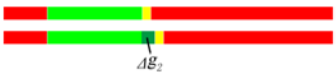

Figure. 1 (b)

When the red light is cut off early, as shown in Figure 1 (a):

$$\begin{cases} y_1 \le x_{1max} \cdot (g_1 + \Delta g_1) / (C + \Delta g_1) \\ y_2 \le x_{2max} \cdot (g_2 - \Delta g_1) / (C - \Delta g_1) \\ \Delta g_1 \ge 0 \end{cases} \tag{3}$$

When the green light is extended, as shown in Figure 1 (b):

$$\begin{cases} y_1 \le x_{1max} \cdot (g_1 + \Delta g_2) / C \\ y_2 \le x_{2max} \cdot (g_2 - \Delta g_2) / C \\ \Delta g_2 \ge 0 \end{cases} \tag{4}$$

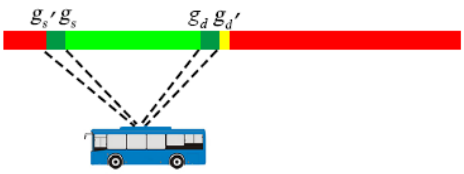

Figure. 2 Signal optimization diagram

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(1) If the bus does not need signal regulation, it can pass through the intersection within the phase green time.

The time when the bus arrives at the intersection stop line is the time when it passes the intersection, $g_s \le S_i \le g_d$:

$$t_i = t_i^{'} = S_i; \quad \Delta h_i = 0 \tag{5}$$

(2) If the bus passes through the intersection after signal control:

① If the red light is cut off early, $g_s^{'} \le S_i \le g_s$:

$$t_i^{'} = S_i; \quad t_i = S_i + \Delta g_1; \quad \Delta h_i = -\Delta g_1 \tag{6}$$

② If the green light is extended, $g_d \le S_i \le g_d^{'}$:

$$t_i^{'} = S_i; \quad t_i = S_i + C - g_1 - \Delta g_2; \quad \Delta h_i = -C + g_1 + \Delta g_2 \tag{7}$$

(3) If beyond the scope of signal control, the bus still needs to stop and wait after arriving at the intersection stop line, $g_d^{'} < S_i < g_s^{'} + C$:

$$t_i^{'} = g_s^{'} + C; \quad t_i = g_s + C; \quad \Delta h_i = g_s^{'} - g_s = -\Delta g_1 \tag{8}$$

2.3 Objective Function

In order to reduce the excessive distance between the front and rear vehicles and other shift vehicles caused by the bus string, the waiting time of passengers at the downstream platform is too long. Therefore, by taking the signal control measures of public transport priority at the intersection, the headway between the front and rear vehicles in this kind of situation is minimized, so as to avoid a large number of passengers caused by long-time waiting and then affect the operation of the subsequent vehicles, or even produce the phenomenon of train string and vicious cycle. Because the signal regulation of the intersection will make the bus pass the intersection ahead of time, the time saved at the intersection $\sum \Delta h_i$ is taken as the objective function.

According to the analysis, when the vehicle can pass the signal light normally, $\Delta h_i = 0$ .But when the vehicle exceeds the regulation range, it can actually be regarded as the control mode of using the red light early break in the next signal cycle.

So the mathematical model is as follows:

$$\begin{cases} min \sum \Delta h_i \\ s.t. \\ (3) \sim (4) \end{cases} \tag{9}$$

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3. Calculation and analysis

3.1 Case Analysis

In order to verify the validity of the model, two intersections with different phases are selected as examples. The bus runs on the bus lane, and the intersection signal is divided into four phases and three phases. The optimized phase is divided into the first phase and the second phase, and the phase saturation $x_{max} = 0.9$, from Table 1 we can see signal timing and intersection flow information.

Table 1 Traffic Flow of Social Vehicles and Signal Timings

parameter	State 1		State 2	
Flow ratio	phase 1	0.25	phase 1	0.16
	phase 2	0.15	phase 2	0.27
	phase 3	0.18	phase 3	0.19
	phase 4	0.12		
Green light interval /s	phase 1	44	phase 1	26
	phase 2	24	phase 2	56
	phase 3	26	phase 3	35
	phase 4	20		
Average saturation		0.81		0.71
Cycle length /s		130		130

Suppose that there are 54 groups of headways generated by 55 shifts of the same line in peak hours, 8 groups of data with headways greater than 1.5 times of the initial headways are selected out, passenger arrival rate $\mu = 1 person / \min$, passenger boarding time $\alpha = 3s / person$, the average operation time from platform 1 to the intersection $\bar{t}_1 = 20s$, the adjustment range of which is $\Delta t_1 \in [-6s, 10s]$ according to the vehicle speed. The time e_i from the beginning of the signal cycle when arriving at platform 1 is randomly generated, as shown in Table 2.

Table 2 Information Generation of Buses

Number	Time difference between arriving at bus stop 1 and starting point of cycle /s	Initial departure interval /s	Actual headway of platform 1 /s	Actual headway of platform 2 /s
1	16	480	850	738
2	50	420	843	780
3	33	420	636	662
4	5	420	798	625
5	125	360	665	639
6	65	480	744	813
7	77	600	912	889
8	109	600	949	862

According to two different signal phase saturation state, state 1 is in high saturation state and state 2 is in low saturation state, the range of advance and extension of optimized phase green light is calculated respectively. In state 1, due to the high phase saturation, the adjustment space is small, the maximum green light advance is 3.1s, the maximum extension is 3.5s; in state 2, the maximum green light advance is 3.5s, the maximum extension is 7.6s.

According to the analysis, the time difference between the bus arrives at the upstream platform of the intersection and the start time of optimization phase $e_i \in [0, C]$. The time difference between the bus arrives at the intersection and the start time of optimization phase $K_i = d_i + \bar{t}_1 - e_i - 130n$, n is a nonnegative integer, $K_i \in [-(C - g_1), C - (\Delta t_{1max} + \Delta g_1)]$. So, when $K_i \in [0, g_1]$, bus passes in green time, $\Delta h_i = 0$;when $K_i \in [-(\Delta t_{1max} + \Delta g_1), 0]$, by the combination of speed regulation and early stop of red light, buses can directly pass through the intersection without stopping, $\Delta h_i = -\Delta g_1$;when $K_i \in [g_1, g_1 - \Delta t_{1min} + \Delta g_2]$, Through the combination of speed regulation and green light extension, public transport vehicles can also smoothly pass the intersection, $\Delta h_i = -C + g_1 + \Delta g_2$;when K_i takes other values, buses must stop and wait for the green light, $\Delta h_i = -\Delta g_1$.

Therefore, according to the calculation, when the intersection is in state 1, vehicle 1 and vehicle 8 accelerate and extend the phase green light, vehicle 4 and vehicle 6 can slow down the speed and control the early break of the red light through the intersection, while vehicle 2, 3, 5 and vehicle 7 need to wait for the green light before passing the intersection. When the intersection is in state 2, vehicles 2 and 7 can directly drive through the intersection by accelerating and extending the green light. Vehicles 3, 4, 5 and 6 are the same as those in state 1, and other vehicles can pass through the intersection within the green light time.

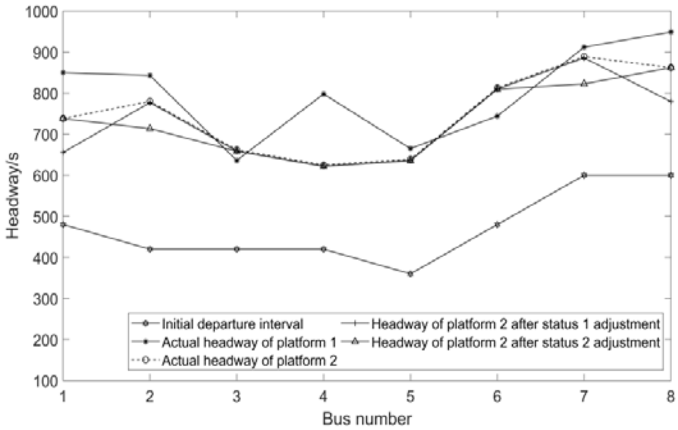

Figure. 3 Comparison Chart of Headway

As shown in Figure 3, the five curves respectively represent the initial departure interval, the actual headway of platform 1 and platform 2, and the headway of the vehicle at platform 2 after state 1 and 2 adjustment. The results show that the delay of vehicles at intersections can be greatly reduced by extending the green light, and the headway can be reduced by 10.3% and 8.0% respectively. However, due to the saturation requirement of the influence phase and in order to reduce the influence on the traffic of other social vehicles as much as possible, and the time of green light advance is limited, so the extent of delay reduction at intersections by the control method of early stop of red light is small, and the headway is reduced by about 0.5%. When the saturation of the front and back phases affected by the optimized phase is low, the adjustment interval is relatively large compared with the high saturation phase.

Through the overall calculation of the model, the average delay of all vehicles passing platform 1 and 2 is reduced by 6.1s and 7.0s. According to the calculation of $E(w)=\frac{E\left(h_i^2\right)}{2E\left(h_i\right)}$, the average waiting time of passengers in the downstream station of the intersection under the two states is reduced by about 3.1% and 2.7%.

4. Conclusion

In this paper, a bus signal priority control model combining speed guidance and signal control is established, and the method to improve the bus bunching is studied under the background of bus lane. Through the optimized phase control of the signal intersection, the bus with large headway can wait as little as possible or not to wait to pass through the intersection, so as to reduce the headway with the front car, avoid the bus bunching phenomenon with the rear car, and also reduce the average waiting time of the downstream passengers at the intersection. The combination of speed regulation and signal regulation makes the vehicle pass through the intersection smoothly, which can reduce the fuel consumption and air pollution to a certain extent. These problems are also worthy of further study.

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