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Headway-Based Multi-Route Transit Signal Priority at Isolated Intersection

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ABSTRACT This article advances the issue of Transit Signal Priority (TSP) control by introducing an application to multi-route bus conflicting requests, capitalizing on the headways and improved total delay of a multi-route bus network. The headway-based TSP accommodating conflicting requests overcomes the shortcoming by the traditional "*First Arrival, First Serve*" strategy and presents significant improvement on bus service performance. According to the bus arrival time, expected headway, and headway deviation value, we establish an optimal signal control model which aiming to minimize the deviation between the bus headway and the expected headway. The case study analysis conducts three schemes: background cycle-based TSP, total delay-based TSP, and headway deviation-based TSP. The performance of headway-based TSP is compared against other two schemes under three different intersection scenarios. The results show that the headway-based TSP has the best effect on improving and balancing the headway stability and distribution. Compared with the scheme of background cycle and the minimum total bus delay, the bus headway deviation is decreased by 42.05% and 28.64% respectively. Compared with the scheme of background cycle, the bus parking delay time is decreased by 36%.

INDEX TERMS Bus priority, vehicle headway, multiple bus conflicting requests, traffic signal control.

I. INTRODUCTION

A. RESEARCH BACKGROUND

Transit Signal Priority (TSP) strategy is widely applied to many urban intersections in China. However, because there are many bus lines in Chinese cities, how to provide bus priority at signalized intersection is a practical problem when multiple buses arrive at the same time and apply for priority in the same cycle. Most of the existing strategies treat all buses with "equal priority" and adopt the "*First Arrival, First Serve*". The main problem with this priority strategy is that it fails to take into account the buses with late departure which need priority more. Some bus lines are often disturbed along the way, which may increase the time interval between the front and behind buses. When the interval between bus and intersection is magnified, the service level is thus decreased. Therefore, it is necessary to consider the priority demand of the "late" and the "large headway" buses in the multi-route bus signal priority control.

B. RESEARCH PROBLEM

This article studies that when buses arrive at the signalized intersection and apply for priority at the same time in a signal cycle, which bus should be selected to carry out priority in the case of not meeting all the requirements? In response to this question, we believe that the "late" or the "large headway" buses should be given a higher "priority". Based on the traditional "*First Arrival, First Serve*" strategy, we introduce the "priority" parameters of the bus in the specific signal control scheme.

The "headway-based priority" is evaluated and implemented in the specific signal control scheme. Bus priority control strategy based on "headway" provides the solution for multiple buses applying for priority at the same time, as well as provide priority services for delayed buses or buses with large headway. The result indicates that this strategy can reduce bus delay and homogenize bus headway.

C. RESEARCH STATUS

The issue of urban congestion in China is becoming more and more critical with the development of economy and the rapid

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increase of private cars. As the most effective way to solve such congestion, public transportation has developed rapidly in recent years, especially the public bus. Many urban intersections have implemented the bus priority signal strategy. However, as there are many bus lines, how to provide bus priority is a practical problem when multiple buses arrive at the same time and apply for priority in the same cycle.

D. RESEARCH OBJECTIVE

On the one hand, the service level of public transport is reflected in the running speed, on the other hand, it is reflected in the interval between the front and behind buses. The purpose of this study is to provide higher priority services for buses with the ''late'' and ''large headway'' so as to reduce the delay of these special buses at intersections.

II. LITERATURE REVIEW

The research on bus control has been carried out for more than 60 years. It has achieved remarkable results in four aspects: priority control strategy, headway research, multi-bus conflicting requests research, and real-time scheduling.

A. BUS PRIORITY CONTROL STRATEGY

Bus signal priority is divided into passive priority, active priority and real-time priority. Passive priority refers to the optimization of the offline signal timing scheme based on the intersection historical traffic data at the same time, regardless of the bus arrival.

Webster [1] and Allsop [2] calculated the delay time of randomly arrived buses in normal phase and delay time in waiting for parking. This model is used as a basic model to study the average delay and per capita delays of buses at signalized intersections. Ludwick [3] proposed to provide the free cable signal control to buses at intersections, and then provide priority according to the bus arrival time, thus the signal light at corresponding time is converted into green light. However, this approach caused delays in private cars and received massive complaints. Viegas and Lu [5] firstly proposed the Intermittent Bus Lane for bus priority control. They (2014) established the model on the premise of the benefit balance between public transport vehicles and social vehicles, comprehensively considered the coordination between intermittent bus lanes and downstream intersection signal control. Based on the randomness of bus arrival and delay, Zeng *et al.* (2014) established a stochastic mixed nonlinear integer programming model (SMNP) to determine the priority of bus priority application, and reduce the delay time of bus passing through the intersection with the best phase division method. Eberlein [8] proposed a real-time control strategy for crossing station (buses skip one or more stops). Chada *et al.* (2001) developed a real-time scheduling strategy for bus stationary, and showed that its performance was better than that of the general non stationary strategy. Daganzo [10] proposed a dynamic control strategy based on headway, which can effectively reduce the amount of slack time in the time schedule. In response to the shortcomings of the traditional bus priority strategy, Yagar S. (1993) provides an improved active priority theory, which take into account both private cars and buses. It not only adopts the conventional bus priority strategies such as green light extension and red light early break, but also proposes to provide greater priority for buses by adjusting the phase sequence of signal intersections. Since the 1990s, theoretical research on real-time priority has gradually replaced active priority as the mainstream research direction. Yagar and Han [21] first carried out the research on real-time signal priority. Based on a variety of decision-making rules, all arriving buses were divided into priority levels, and multiple groups of different signal control schemes were generated. The simulation was implemented by using the field data of the trunk intersection of Queen Street in Toronto as an example. The results show that the total delay of buses has been effectively improved.

B. BUS HEADWAY

Furth and Muller [12] gives priority to the buses with large headway rather than the early arrival ones in order to ensure the uniform distribution of the bus lines. van Oort *et al.* [23] conducted a research on the phenomenon of ''large interval'' and ''bus train'' in bus lines. We found that buses with large headway will stop at the downstream platform for a longer time due to the increase of delayed passengers, which will result in the ''bus train'' with front buses and ''large interval'' with behind buses. In the basis of using three bus priority control strategies, the current research mainly focus on giving priority to single bus whose headway exceeds the threshold.

C. MULTIPLE BUS CONFLICTING REQUESTS

In view of the multiple bus conflicting requests, the earliest way to solve this problem is through ''*First Arrival First Serve''* strategy. The optimization research is proposed later based on the minimum delay between multiple buses, the minimum delay of passengers, the minimum delay between buses and social vehicles, as well as the priority decision, rolling optimization and so on. Chang *et al.* (1996) consider that when there are multiple bus requests for priority in the same cycle, the ''*First Arrival First Serve''* method shall be adopted to provide priority services for the earliest bus arriving at the intersection, and then buses arriving later shall be considered according to the order. Hu *et al.* [32] overcome the shortcomings of the traditional *''First Arrival First Serve''* method, and put forward the method of redistributing the green light time without changing the cycle length to provide priority for delayed buses. Ma *et al.* [30] propose a signal control model for multiple bus priority conflicting requests to maximize the green time availability for buses and without causing excessive congestion to other vehicles.

D. REAL-TIME SCHEDULING

There are three main reasons for the deviation of bus line punctuality rate: travel time, platform stop time, and intersection waiting time. The headway of the bus can be evenly distributed by controlling the stop time of the bus platform according to the bus is on time or not. Christofa and Skabardonis [24] propose a scheduling model based on the actual deviation of bus punctuality according to platform stop time, passenger demand and intersection waiting time. Daganzo and Pilachowski [25] put forward an adaptive control strategy based on the coordination of buses and the shift value of timetable, which can adjust the running speed of the front and behind buses in real time. Yin W. (2018) optimizes the headway research by using the data in the automatic vehicle location (AVL) system and taking headway stability as the control objective.

Generally speaking, the existing research on public transport priority ignores the factors of early arrival and late arrival buses. The research on the key factors such as public transport service level and headway is still relatively small.

III. MULTI-ROUTE BUS PRIORITY CONTROL STRATEGY

A. DEFINITIONS

1) ROLLING TIME WINDOW

The rolling time window method is adopted in this study in the consideration of the latest arrival buses at the intersection in real time. The rolling period length is the cycle, that is to say, only the bus arriving within the maximum cycle need to be optimized.

2) PRIORITY CONFLICTS

When buses arrive at the same signalized intersection and ask for priority at the same time in the same time window.

3) BUS HEADWAY

The bus ‘‘headway’’ is defined as the time interval between two buses before and after arrived at intersection in the same bus line. It consists of three parts: the driving time of the distance, the total stopping time of each bus stop, and the delay time of the parking line at the intersection.

B. BUS PRIORITY SIGNAL CONTROL STRATEGY

1) CONTROL OBJECTIVES

The capacity of a single bus is much higher than an ordinary car, thus optimizing the uniformity of bus headway distribution can not only improve the bus service level, but also improve the reliability and attractiveness of public transportation. In order to avoid intersections congestion caused by the large number of social vehicles queuing due to bus priority, this article sets a bus priority control objective based on headway (minimum deviation between vehicle headway and expected headway), and optimizes the timing scheme of bus priority signal control.

2) CONTROL FRAMEWORK

The control framework is designed to provide effective priority control for multiple bus needs at the intersection, while minimizing the negative impact on the entire intersection of the control system. It consists of two key modules: system interference minimization and service order optimization.

a: SYSTEM INTERFERENCE MINIMIZATION

The main reason for the failure of most bus priority schemes is that the influence of social vehicles traffic volume on bus priority is not taken into account in the bus timing schemes optimization. In order to solve the problem, the system disturbance minimization module is proposed to guarantee signalized intersection operates under the acceptable saturation. Under this condition, there will be no queuing and excessive congestion at signalized intersections caused by bus priority control. In the basis of historical traffic data and real-time traffic data at intersections, this model can obtain the minimum green-light duration of each intersection phase, which constitutes the minimum green-light cycle-background timing scheme.

b: SERVICE ORDER OPTIMIZATION

Service order optimization conducts the constraints of the system interference minimization module as input to solve the optimal signal timing and bus service order when there are multiple priority requests conflict in a cycle.

In addition, the framework assumes that parameters such as optimal signal plan and saturation threshold corresponding to general traffic demand in each cycle can be set as fixed values according to historical data or as dynamic values based on real-time traffic volume.

IV. MULTI-ROUTE BUS PRIORITY REQUISITION CONFLICTS MODEL

A. ASSUMPTIONS

(1) The intersections studied in this article are standard plane intersections. All four entrance roads are equipped with bus lanes. When buses enter the intersection, the queuing problem of social vehicles is not considered.

(2) On the premise of not changing the basic signal control phase structure (phase number and phase order), only the green light extension and red light early break approach will be considered. The start and stop time of green light in each phase is integrated and optimized in order to reduce the departure deviation of bus headway and expected headway when it leaves the intersection.

(3) Buses are equipped with GPS positioning system, which can transmit real-time information such as position, speed, number, and other information in real time. It is assumed that the arrival time at the intersection parking line with constant speed can be predicted.

B. MODEL CONSTRUCTION

In general, the signal optimizer generates the bus request priority scheme when the green light time of the previous phase ends or the green light time of the next phase starts. Based on this feature, we transform the optimization problem of multi-route bus request service order into a multi-phase decision-making problem by constructing a model. For signalized intersections, there are four basic decision-making stages (stage 1, stage 2, stage 3, stage 4) in four phases of a cycle, and each decision-making stage is related to the signal phase. Any stage of any phase is adjusted by inserting the maximum available time into the two decision-making stages in the basis of related phase. The phase length is constrained by the minimum required green light time and the maximum green light extension time.

In addition, priority requests can be served by different priority strategies. This model mainly considers the strategies of green light extension and red light early break. This article gives an example of bus priority in the first phase under two strategies.

1) CONSTRAINTS

L_b is the distance between bus b and the intersection stop line; v_b is the running speed of bus b; T_{bac} is the arrival time when bus b reaches the intersection stop line at the speed of v_b; T_{blc} is the leaving time when bus b leaves the intersection parking line. The actual arrival time of bus b at the intersection parking line is:

$$T_{bac} = T_{blc} + \frac{L_b}{v_b} \tag{1}$$

We assumed that social vehicle traffic flow can be predicted and evenly arrived within one cycle. When there is no bus priority application in this cycle, the signal timing only needs to satisfy the traffic of social vehicles, this is called background signal. In a four-phase intersection, the phase length of its background signal is g_i ($i = 1, 2, 3, 4$, the same below). The interval between phase i and the next phase is I_i; Phase i has a green light start time of g_{is} and a green light end time of g_{ie}; Δt_i is the green light extension time of phase i ($0 \le \Delta t_i \le t_i^{+}$), that is,

$$g_{ie} = g_{is} + g_i + \Delta t_i \tag{2}$$

$$g_{(i+1)s} = g_{ie} + I_i \tag{3}$$

When adjusting the green light time, it is necessary to consider the impact on social vehicles, that is, the saturation of each phase and the total length of the cycle should have an upper limit. The total cycle duration cannot exceed the upper limit C_{max}, and the maximum saturation per phase cannot exceed x_{max}, thus,

$$g_{4e} + I_4 - g_{1s} \le C_{max} \tag{4}$$

$$x_i = \frac{q_i(g_{ie} - g'_{ie})}{Q(g_{ie} - g_{is})} \le x \quad i = 1, 2, 3, 4 \tag{5}$$

Here, q_i is the traffic flow of phase i; Q is the periodic traffic flow rate; g_{iE} is the green light end time of phase i in the previous cycle.

2) VEHICLE DEPARTURE TIME AT INTERSECTION

The application cycle period is set as k in i phase. Assuming it passes in two cycles, otherwise this cycle will be discarded. For bus b, whether it can pass through this cycle is divided into two situations: when the actual arrival time of bus b is before the end of cycle k in phase i, bus b can pass through in cycle k, where $f = 0$; when bus b actual arrival time is after the end of cycle k in phase i, bus b can pass through in cycle $k+1$, where $f=1$.

$$f = \begin{cases} 0 & T_{bac} \le g_{ike} \\ 1 & g_{ike} < T_{bac} \le g_{4ke} + I_{4k} + \sum_{j=0}^{i-1} \left(g_j + I_j\right) + g_{i(k+1)} \end{cases} \tag{6}$$

When $f=0$, that is, when bus b passes through this cycle ($T_{bac} \le g_{ie}$), its actual departure time from the intersection can be divided into two situations, as shown in equation 7:

$$T_{blc} = \begin{cases} g_{iks} & T_{bac} \le g_{iks} \\ T_{bac} & g_{iks} \le T_{bac} \le g_{ike} \end{cases} \tag{7}$$

When bus b arrives before the green light start time of cycle k in phase i, $T_{bac} \le g_{iks}$, thus the departure time is the green light start time of cycle k in phase i, $T_{blc} = g_{iks}$; when the bus b arrives during green light period of cycle k in phase i, $g_{ikS} \le t_{bac} \le g_{ikE}$, it arrives at the green light, so $T_{blc} = T_{bac}$.

When $f = 1$, when bus b passes in the cycle $k + 1$ (assuming the next cycle runs based on the basic signal timing), its actual departure time T_{blc} from the intersection is (8), as shown at the bottom of the page.

When bus b arrives before the green light starts of the cycle $k+1$ in phase i, that is, $g_{ike} \le T_{bac} \le g_{4e}+I_4+\sum_{j=0}^{i-1}\left(g_j + I_j\right)$. Then the departure time is green light start time of cycle $k+1$ in phase i, which is $g_{4e} + I_4 + \sum_{j=0}^{i-1}(g_j + I_j) \le T_{bac} \le g_{4e} + I_4 + \sum_{j=0}^{i-1}(g_j + I_j) + g_i$. It arrives at the green light, so $T_{blc} = T_{bac}$.

3) THE OBJECTIVE FUNCTION OF MINIMIZING TOTAL BUS DELAY

Parking delay of bus b at the intersection is D_{bc}, that is,

$$D_{\mathrm{bc}} = T_{blc} - T_{bac} \tag{9}$$

Under the conflict of multiple bus requests at intersections, the objective function of minimizing total bus delay is:

$$\min \sum_{b} D_{bc} \tag{10}$$

4) THE OBJECTIVE FUNCTION OF MINIMIZING TOTAL BUS HEADWAY DEVIATION

When bus b arrives at the intersection, the headway with the front bus is H_{bac}. The deviation value of bus headway in the objective function is defined as the absolute value of bus headway H_{bac}, plus the increment value D_{bc} (the headway caused by the delay during the parking waiting period), and minus the expected headway $\overline{H}_b$. Therefore, the final objective function based on the minimum deviation of overall bus

$$T_{blc} = \begin{cases} g_{4e} + I_4 + \sum_{j=0}^{i-1} \left(g_j + I_j\right) g_{ike} \le T_{bac} \le g_{4e} + I_4 + \sum_{j=0}^{i-1} (g_j + I_j) \\ T_{bac} g_{4e} + I_4 + \sum_{j=0}^{i-1} (g_j + I_j) \le T_{bac} \le g_{4e} + I_4 + \sum_{j=0}^{i-1} (g_j + I_j) + g_{i(k+1)} \end{cases} \tag{8}$$

TABLE 1. Location of intersections and bus stops.

Number	1	2	3	4
*Intersection location (m)	384	1384	2084	-
Bus stops location (m)	518	1256	1898	2695

*Note: Intersection and bus stop location in this table are the distance from the starting point.

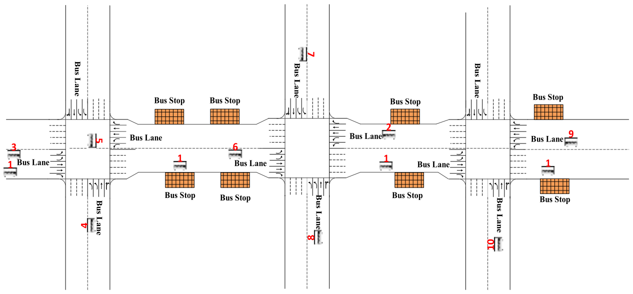

FIGURE 1. Schematic diagram of intersections and bus routes.

headway is as follows:

$$\min \sum_{b} |H_{bac} + D_{bc} - \overline{H}_b| \tag{11}$$

V. CASE STUDY

A. BASIC CONDITION

1) INTERSECTION AND STOP

This study selects a main line section with bus priority lane as a case study in order to illustrate the applicability of headway-based multi-route bus conflicting requests priority control model. Three continuous signalized intersections in the main road section are selected and the left boundary is set as 0 meters. From left to right, they are recorded as intersection 1, intersection 2 and intersection 3 in sequence. The distance between intersection 1 and intersection 2 is 1000 meters, the distance between intersection 2 and intersection 3 is 700 meters, the coordinate positions are shown in Table 1. The main line section as shown in Figure 1 which contains four bus stops in one direction and numbered as stop 1, stop 2, stop 3, and stop 4 from left to right.

The position information of intersections, the route of bus lines 1-10 and the location of bus stops are shown in Figure 1.

2) INTERSECTION AND STOP

The bus lines at single intersections and bus departure frequency is increased in order to highlight multi-route bus conflicting requests at intersections. Therefore, multi-route bus conflicting requests are intensified at intersections, the efficiency of the model can be proved in a short time.

The basic parameters of bus lines required for this study are: expected headway, passing intersection number, application phase of the intersection, theoretical arrival time, arrival headway deviation, and actual arrival time. We assumed that the front vehicles arrive at the intersection is on time in order to simplify the study.

Expected headway is the same as the departure frequency of the bus. The departure frequencies (expected headway) of 10 lines selected in this article are shown in the Table 2.

TABLE 2. Bus line departure frequency.

Route number	1	2	3	4	5	6	7	8	9	10
Departure interval/s	100	90	120	120	180	110	120	150	90	120

TABLE 3. Basic data of line 1.

Vehicle number	Inter-section	Theoretical arrival time(s)	Expected headway (s)	Apply for phase	Arrival headway deviation (s)	Actual arrival time(s)
4	1	10	100	2	8	18
4	1	110	100	2	59	169
6	1	210	100	2	60	270
7	1	310	100	2	-35	275
8	1	410	100	2	-16	394
9	1	510	100	2	5	515
10	1	610	100	2	-54	556

TABLE 4. Results based on background cycle.

Bus Line	Intersection	Expected headway(s)	Apply for phase	Total Delay(s)	Total deviation of headway(s)
1	1	100	2	264	291
1	2	100	2	275	540
1	3	100	2	110	346
2	2	90	2	276	332
3	1	120	1	252	144
4	1	120	3	271	272
5	1	180	4	59	173
6	2	110	1	150	361
7	2	120	3	181	237
8	2	150	4	134	200
9	3	90	1	149	294
10	3	120	3	206	180
Total				2327	3370

These are the intersection numbers applied for access. We assumed that there are 3 to 5 bus lines passing through each intersection, of which line 1 passes through intersection 1, 2 and 3.

Arrival headway deviation value is the deviation between headway of bus arrival at stop line with front bus and the expected headway. In this study, the headway deviation value is simulated by normal distribution. With reference to the parameter value design of Ma Wanjing (2013) on the punctuality rate, the mean value is 25s, the standard deviation is 90s, and it is randomly generated. Finally, data with a greater deviation value than the headway is rejected as invalid data. Line 1 is taken as an example in Table 3.

B. RESULTS

The intersection delay, headway deviation, and other parameters are calculated under the 600s signal timing scheme of each intersection. The calculation results of the three schemes are shown in Table 4, 5, and 6.

1) THREE CONTROL SCHEMES

a: BASE ON THE BACKGROUND CYCLE

The total parking delay of buses passing through three intersections is 2327s, and the total headway deviation is 3370s. Details are shown in Table 4.

b: BASED ON THE MINIMUM TOTAL VEHICLE DELAY

Based on the multi route priority control model with minimum delay, the total parking delay of buses passing through

TABLE 5. Results based on minimum total delay.

Bus Line	Intersection	Expected headway(s)	Apply for phase	Total Delay(s)	Total deviation of headway(s)
1	1	100	2	109	314
1	2	100	2	170	343
1	3	100	2	0	246
2	2	90	2	46	168
3	1	120	1	110	294
4	1	120	3	22	148
5	1	180	4	27	179
6	2	110	1	268	451
7	2	120	3	40	146
8	2	150	4	75	147
9	3	90	1	26	231
10	3	120	3	42	70
Total				935	2737

TABLE 6. Results based on minimum headway deviation.

Bus Line	Intersection	Expected headway(s)	Apply for phase	Total Delay(s)	Total deviation of headway(s)
1	1	100	2	60	189
1	2	100	2	35	190
1	3	100	2	95	227
2	2	90	2	41	247
3	1	120	1	212	168
4	1	120	3	160	97
5	1	180	4	184	122
6	2	110	1	89	272
7	2	120	3	70	126
8	2	150	4	72	138
9	3	90	1	194	151
10	3	120	3	110	26
Total				1322	1953

TABLE 7. Optimization calculation results based on minimum total delay.

	Background period(s)	Minimum total bus delay(s)	Minimum headway for multi-route buses(s)
Total parking delay	2327	935	1322
The headway deviation	3370	2737	1953

three intersections is 935s, and the total headway deviation is 2737s. Details are shown in Table 5.

c: BASED ON THE MINIMUM HEADWAY DEVIATION

Based on the multi route priority control model with minimum headway deviation, the total parking delay of buses passing through three intersections is 1322s, and the total headway deviation is 1953s. Details are shown in Table 6.

2) COMPARATIVE ANALYSIS OF OVERALL RESULTS

The calculation results of the three schemes are shown in Table 7.

Based on the background period, for buses arriving at the intersection and passing within 600s, the total parking delay at the intersection is 2327s, and the total deviation between the headway and the expected headway is 3370s.

Based on the multi-route bus conflicting requests model with minimum delay, for buses arriving at the intersection and passing within 600s, the total parking delay at the intersection is 935s, and the total deviation between the headway and the expected headway is 2737s. Compared with the background timing scheme, the total bus delay at intersections decreased by 59.82%, and the headway deviations decreased by 18.78%. The result shows that the bus delay optimization approach has significant effect at intersections, as well as the headway deviation.

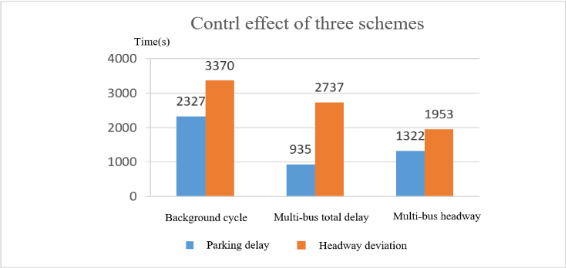

FIGURE 2. Control effect of three schemes.

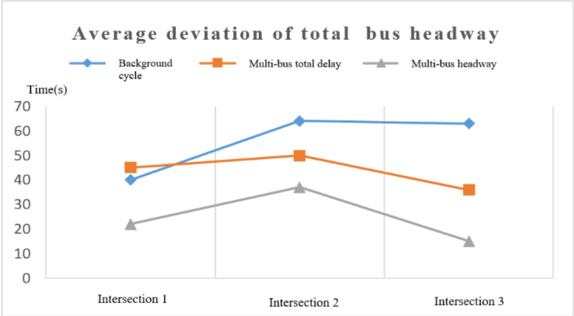

FIGURE 3. Average deviation value of bus headway.

According to the headway-based multi-route bus conflicting requests model, for buses arriving at the intersection and passing within 600s, the total parking delay at the intersection is 1322s, and the total deviation between the headway and the expected headway is 1953s. Compared with the background cycle scheme, the total bus delay at intersections decreased by 43.19%, and the total deviation of headway decreased by 42.05%. Compared with the minimum total delay, the total bus delay at intersections increased by 29.27%, however the total deviation of headway decreased by 28.64%.

To sum up, the multi-route bus conflicting requests model with the minimum delay has the best effect on bus delay optimization, while it also reduces the deviation headway. The headway-based multi-route bus conflicting request model has a significant effect on reducing the headway deviation. It can selectively reduce the bus delay at intersections, so that the distribution of buses on the same line is more uniform.

As shown in Figure 3, the absolute value of vehicle headway deviation is averaged by three intersections in three schemes. We can see that the headway-based multi-route model has the best effect, and the average headway deviation after passing through the signalized intersection is basically less than 30s. The multi-route model with minimum bus delays has better effect, we can see that the headway departure value can be controlled to a certain extent under the condition of giving priority to all buses.

3) COMPARATIVE ANALYSIS OF VARIOUS LINES

a: LINE 1 OPTIMIZATION ANALYSIS

For all buses of line 1, the average headway deviation in Figure 4 is calculated by the three schemes according to the departure time at intersection 1, 2 and 3.

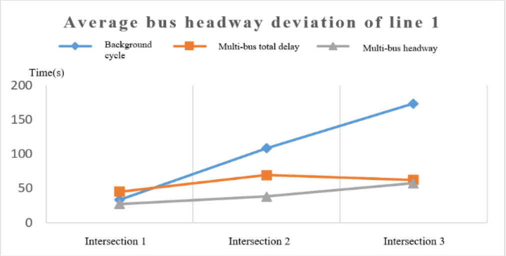

FIGURE 4. Average bus headway deviation of line 1 under three schemes.

TABLE 8. Bus headway of line 4 under various schemes.

Bus number	Arrival headway(s)	Background period(s)	Minimum total delay(s)	Multi-route bus headway(s)
No.17	161	240	161	161
No.18	51	120	51	144
No.19	133	20	133	133
No.20	88	88	110	129
No.21	105	160	105	130

As can be seen from the Figure 4, the average headway deviation based on multi-bus headway optimization is slightly better than that based on single-line headway. Thus, the optimization effects are similar. Based on the minimum multi-route total delay, the average headway deviation rate is higher than that based on multi-route bus. The optimized headway deviation is about 40 ∼ 60s.

Since the background period is a fixed period and only historical traffic data at intersections are considered, the difference is the greatest between average headway and expected headway. Meanwhile, due to the fixed cycle, it cannot be optimized according to the arrival time and headway. Therefore, under the background cycle scheme, the more intersections that line 1 passes through, the worse controllability of the headway deviation is, and it is prone to further deterioration.

b: LINE 4 OPTIMIZATION ANALYSIS

As shown in Table 8, the headway of 5 buses in Line 4 is compared based on three optimized conditions, and a graph is proceeded as Figure 5. We can see that the optimization solution based on the multi-route bus headway has the minimum deviation, best effect and stability, which is close to the expected headway of 120s. The solution based on the minimum total delay of multiple buses takes second place, while then solution based on the background period is the worst.

According to Figure 5, the headway of bus 18 is increased after optimization with the minimum delay model. In the basis of relevance data, it is found that the application phase is 3, the arrival time is 81, the headway between the arrival bus and the front bus is 51, and the expected headway is 120, which almost results in the phenomenon of bus "train".

Based on the method of minimizing bus delay, bus 18 meets the condition of green light extension priority, it can be given priority to pass through the intersection directly in the first cycle. In this case, the parking delay at the intersection is 0, but the headway is not optimized yet.

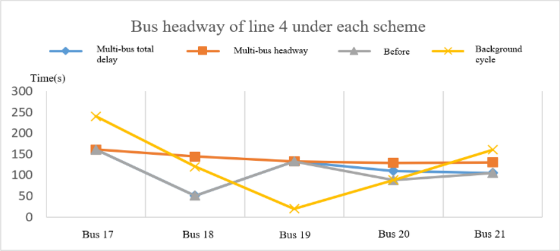

FIGURE 5. Average bus headway deviation of Line 4 under three schemes.

In the headway based multi-route bus conflicting requests model, its headway is 51, which deviates from the expected headway by 69. If the priority is not given to the bus and it has to pass from the next cycle, that the headway is 144 and the deviation is 24. This result shows that the bus priority control can enhance the vehicle headway uniform under certain conditions.

VI. CONCLUSION

In this research, a headway-based priority control method is proposed for multiple conflicting TSP requests in a single intersection. This method overcomes the challenge born by the conventional "First Arrival, First Serve" strategy and presents significant improvement on bus service performance. The feature of headway-based control can be combined with the priority strategy of green light extension and red light early break, and make the overall headway much closer to the expected headway. Therefore, the phenomenon of "bus train" and "large headway" can be improved, as well as the service level and attractiveness of buses.

Three optimization models of background cycle, minimum total bus delay, and minimum headway deviation are compared and analyzed in this article. The model based on the minimum total bus delay has the best efficiency in reducing bus delays at intersections. Compared with the background cycle and the multi-bus headway optimization, the delay is decreased by 59.82% and 29.27% respectively. The model based on the minimum headway deviation has the best effect on improving the headway stability and uniform distribution. Compared with the background cycle and the minimum total bus delay optimization, the headway deviation is decreased by 42.05% and 28.64% respectively. Compared with the background cycle, the bus parking delay is decreased by 36%.

In conclusion, the headway based multi-route bus conflicting requests model shows good adaptability when there are delayed buses, large headways, and long waiting time. It can not only effectively control vehicle delay at intersections, but also give priority to buses "selectively" according to the headway. Furthermore, the overall headway balance and stability of all bus lines at intersections can be greatly enhanced.

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