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Multi-phase bus signal priority strategy at isolated intersections

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Abstract: To satisfy the multiple priority requests from buses that arrive at different phases within a small time window, a multi-phase bus signal priority (MPBSP) strategy is developed. The proximity principle is brought forward to settle the conflicts among multiple priority requests and arrange the optimal priority sequence. To avoid over saturation of the intersection, a conditional MPBSP algorithm that adopts early green and green extension strategies is developed to give priority to the bus with the highest priority level when green time that each phase runs makes its saturation degree not larger than 0.95. Finally, the algorithm is tested in the VISSIM environment and compared with the normal signal timing algorithm. Sensitive analysis of the number of priority phases, bus demand, and volume to capacity ratios are conducted to quantify their impacts on the benefits of the MPBSP. Results show that the MPBSP strategy can effectively reduce bus delays, and with the increase in the number of priority phases, the reduction range of bus delays also increases.

Key words: bus signal priority; multiple phases; early green; green extension; isolated intersection

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Bus signal priority (BSP) is viewed as an important way to reduce traffic congestion in many Chinese cities, such as Beijing and Shanghai. The bus networks of these cities have two obvious characteristics. One is the existence of many bus routes and buses. For example, there are more than 880 bus routes and 28 000 buses in Beijing[1]. The other is the high bus frequency. In rush hours, bus headways of most routes are smaller than 3 min and even in off-peak hours some bus headways are smaller than 5 min. So for the signal intersections of central areas, it is quite common that more than one bus arrive at the same intersection from different directions within a small time window. In view of the complex circumstances, traffic engineers face difficulty in dealing with multiple priority requests and the difficulty may affect the improvement of bus benefits when implementing BSP strategies.

Numerous studies have already been conducted in BSP strategies. However, a common characteristic of these studies is that much attention is centered on the single-phase bus signal priority (SPBSP), which provides priority to buses in a given phase that has the highest bus frequency among all the phases and ignores arrival buses in other phases because of their low bus frequencies[2–5]. There is no priority request conflict among arrival buses because these vehicles place requests to the same phase. This strategy is reasonable when there are large differences among bus frequencies of all phases, otherwise it cannot benefit most buses, and it is not efficient. In such circumstances, a multi-phases bus signal priority (MPBSP) strategy which can provide priority to more buses is needed to extend the application circumstances of the BSP.

Multiple priority requests can occur when several buses approach an intersection from different directions in a short period of time. It is possible that one or more buses in other phases place priority requests before completing current priority services for buses that have arrived earlier, and thus conflicts among multiple requests are generated. How to determine phase durations to best serve the priority requests is the main problem of the MPBSP. Compared with many achievements in the SPBSP strategy, there are few studies conducted on the subject of MPBSP. Head et al.[6] found that a first-come, first-served policy for serving multiple priority requests cannot achieve optimal control benefits by way of example. Actually, the first-come, first-served policy can make sense in the queuing theory because the following vehicles cannot pass its lead vehicles to receive service in advance. Nevertheless, in the BSP system, the late arrivals may clear the intersection earlier than the early arrivals, because traffic lights of all the phases switch to green in a fixed sequence and a bus which arrives earlier may encounter a green light later. Li[7] proposed a two-dimensional conflict matrix to depict the conflicting situation between major street requests and minor street requests, which can determine the optimal priority strategy for a BSP problem with two requests. The matrix can deal with priority requests from two phases and with the increase in priority phases, the number of dimensions also increases, which results in much difficulty in obtaining optimal solutions. Ma and Yang[8] developed a model to arrange multiple bus priority requests based on dynamic programming, which can reduce total person delay and vehicle delay. However, the model must obtain the arrival times at the stop line of buses accurately at least one cycle length ahead, which is impossible at present.

Due to the particularity of the MPBSP, this paper attempts to develop a dynamic algorithm to treat the problem of multiple requests based on the traditional vehicle detection methods such as inductive loops, which can be used at isolated signalized intersections.

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1 Methodology Development

1.1 Proximity principle

The main problem of the MPBSP algorithm is to settle the conflicts among multiple requests and determine the priority sequence according to individual priority levels. When providing priority to one bus, the time points when buses of other phases are granted priority will be inevitably postponed. The benefits of all buses have an inversely proportional relationship with the postponed time duration. The bus with the highest priority level should be set as the one which has the smallest negative impact on other buses, and in this way the benefits of all buses can be maximized. Only when traffic lights turn green can a bus clear the intersection, so the bus priority level is closely related to the time interval between its arrival time point and the starting time point of the next green phase, because a shorter interval results in less postponed time durations of other buses.

Based on the above analysis, the proximity principle is brought forward to describe the relationship clearly and it includes three elements: 1) A bus requesting during a green phase has a higher priority level than the one requesting during a red phase. 2) If a bus requests during a red phase, the shorter the time interval between its arrival time and its next green phase starting time is, the higher its priority level is. 3) If buses request at the same phase, the earlier the first bus arrives, the higher its priority level is. In this way, the priority sequence of multiple requests is arranged. Buses that have placed requests will be granted priority in turn according to the priority sequence and no request is rejected.

For example, as described in Fig. 1, one signal intersection has four phases and the current green phase is phase 2. During the time period of 35 to 50 s, bus 1 (B_1) of phase 1, bus 2 (B_2) and bus 3 (B_3) of phase 2, bus 4 (B_4) of phase 3, and bus 5 (B_5) of phase 4 place priority requests, respectively. B_2 arrives at the intersection earlier than B_3. According to the proximity principle, the priority levels of the five buses are $B_2 > B_3 > B_4 > B_5 > B_1$.

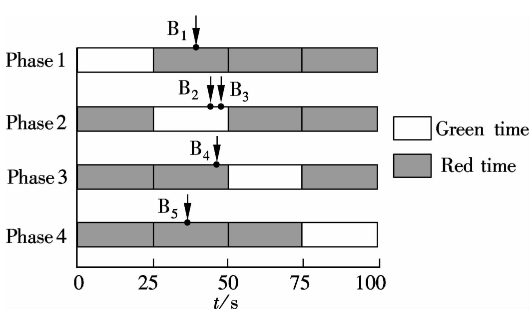

Fig. 1 Illustration of proximity principle

1.2 Algorithm construction

The MPBSP algorithm at isolated intersections operates in an acyclic manner and aims to speed up bus service with less negative impacts on the general traffic. The algorithm depends on the selective vehicle detection system with a radio frequency tag instrumented on the bus and an inductive loop located 100 m away from the approach stop line to detect the presence of buses. Each bus can trigger a priority request when passing over the bus detector. Besides, the second group of inductive loop detectors 40 m upstream of the stop line is placed on each approach in order to collect traffic volume in fixed time intervals.

The MPBSP decision scheme incorporates two classic strategies:

1) Green extension If a bus checks in at green phase and cannot pass the stop line before the ending of the green phase, a green extension will be given to it. The green phase for the bus will be extended confined by the maximum green extension.

2) Early green (or red truncation) If the signal phase is yellow or red when the bus checks in, the red phase will be truncated with a time interval, taking into consideration pedestrian walk and queue service.

The BSP strategy usually results in negative impacts on general traffic, such as the increase in vehicle delay and saturation degree, and even on queue spillovers of non-priority phases. It is true that the BSP strategy can improve the efficiency of passenger service; however, in the authors' opinion, the normal operation of the traffic order is more important than the provision of the BSP. A BSP strategy which results in the chaos of the traffic order is not recommended. The basic premise of applying the BSP strategy should be the regular operation of the traffic flow. Therefore, in this study, a conditional priority strategy is adopted to reduce the negative impacts on general traffic. The green time that each phase runs should make its saturation degree no larger than one threshold value. In this study, the value is recommended as 0.95, because usually one phase is in an undersaturated condition when its saturation degree is not larger than 0.95.

The flow chart of the algorithm is shown in Fig. 2, and it is incorporated into a signal controller. The algorithm updates priority levels of arrival buses in real time (e. g. every 0.1 s) to achieve maximum control benefits. The bus arrival time prediction module, the green extension module and the early green module are three key components of the algorithm and they are described as follows.

1.2.1 Bus arrival time prediction module

Accurate prediction of the bus arrival time at the stop line is a vital element in the BSP system. Liu et al. [9] used inductive loops to detect the bus presence, and divided bus travel time from the detected location to the stop line into two parts: time waiting for the green phase and time needed to clear the queue in front of the bus. Travel time is a function of traffic demand, queue length, current signal timing and time point of bus. We conducted several field experiments at a signal intersection to evaluate the performance of the algorithm. The intersection is located in one of the busiest districts in the city of Changchun, China. Results show that the algorithm provides an acceptable accuracy, which can be used for the BSP. Due to the length limit, the MPBSP strategy directly adopts the prediction algorithm and we do not explain the formulation of the algorithm in detail in this paper. Readers can refer to Refs. [9 - 10].

1.2.2 Green extension module

If a bus arrives at a green phase and cannot pass the stop line before the ending of green phase, a green extension will be adopted to give it priority. Take a signal intersection that has n phases as an example to explain the module. The cur-

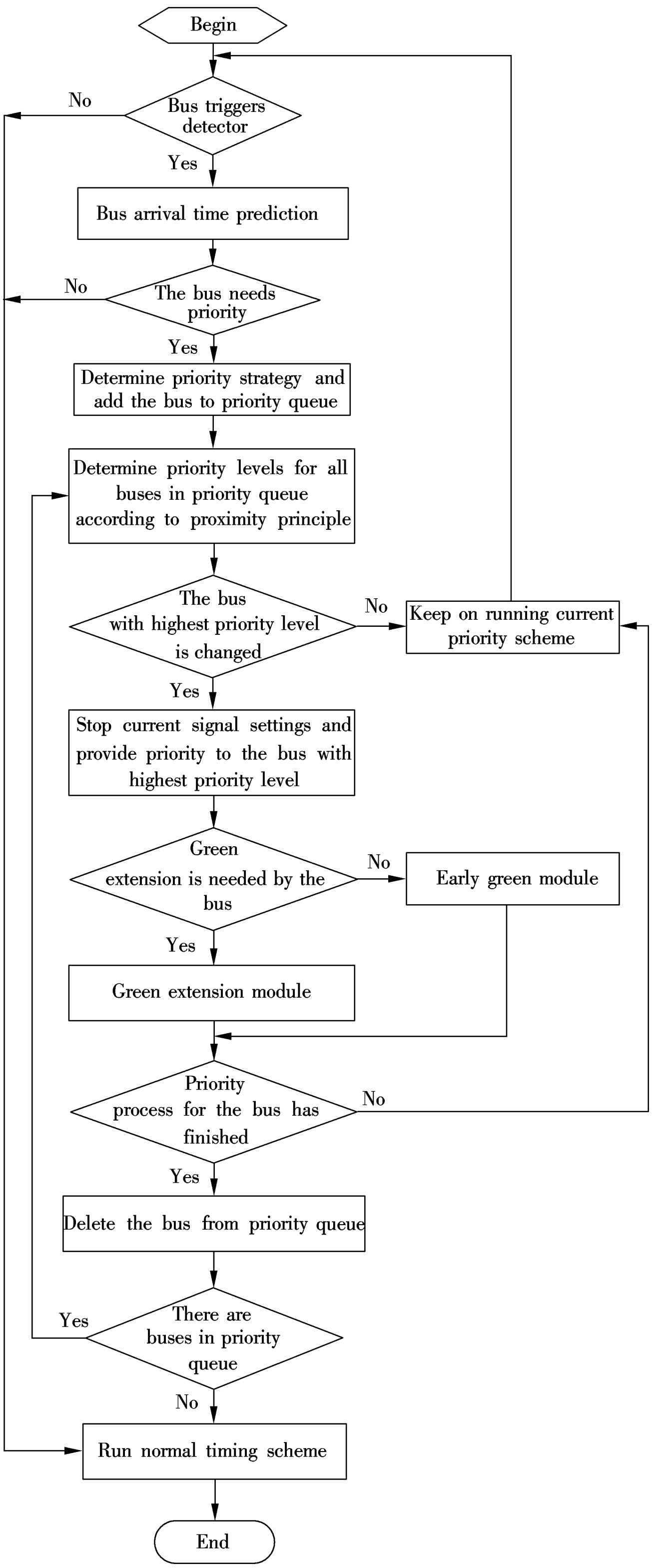

Fig. 2 Flow chart of MPBSP algorithm

rent green phase is phase i and the ending time of its green light is T_1. Bus B_i of phase i places a priority request and its arrival time at the stop line is T_2. When $T_1 \geqslant T_2$, the signal controller will run normal signal settings, otherwise a green extension will be requested.

The extension time that is requested by B_i is G_{Ei} and it is equal to $T_2 - T_1$. The allowable extended green time of phase i is denoted as G_{Ai}, and it can be calculated by

$$G_{Ai} = G_{Ei\max} - G_{Ei} \tag{1}$$

where $G_{Ei\max}$ is the maximum green extension time of phase i, s; G_{Ei} is the elapsed extension time of phase i in this cycle when B_i arrives at the intersection, s. If no green extension has been conducted in this cycle, it is equal to 0.

When $G_{Ai} \geqslant G_{Ei}$, a green extension can be implemented; otherwise, the priority request will be postponed to the next cycle and in this cycle the signal controller runs normal signal settings.

$G_{Ei\max}$ is one important parameter of the green extension module. Many methods have been presented theoretically to determine it. To the authors' knowledge, there is not a universal method to determine the maximum green extension time because it is closely related to real traffic states. The longer the maximum green extension time, the greater the impacts on cross street traffic. Especially in the MPBSP algorithm, each phase has an opportunity to extend its green light due to the requests from multiple directions. So the maximum green extension time of each phase should be controlled and in this study we set it as 10 s by referring to previous studies.

Once one phase is extended, some more vehicles may arrive on other approaches during the red time. Unreasonable green time allocation of the following phases may result in over saturation and queue spillovers. To minimize the above negative impacts, a conditional priority strategy is applied. Take the following phase j as example. Notation x_{pj} is denoted as the threshold value of 0.95 of phase j, and it can be calculated by

$$x_{pj} = \frac{(R_j + g_{jp}) q_{j,t}}{g_{jp} S_j} \tag{2}$$

where R_j is the elapsed time period between the ending time of the last green light and the starting time of the present green light of phase j, s; S_j is the saturation flow rate of the critical lane of phase j, pcu/s; $q_{j,t}$ is the flow rate of the critical lane of phase j in the data sampling interval t, pcu/s; g_{jp} is the green time that makes the saturation degree of phase j equal x_{pj}, s.

A three-term moving average is used to estimate $q_{j,t}$ to eliminate the dynamic fluctuation of the general traffic.

$$q_{j,t} = \frac{q_{j,t-1} + q_{j,t-2} + q_{j,t-3}}{3} \tag{3}$$

Considering the limitation of the minimum green time, g_{jp} can be calculated by

$$g_{jp} = \max\left(\frac{R_j q_{j,t}}{x_{pj} S_j - q_{j,t}},\ g_{j\min}\right) \tag{4}$$

where $g_{j\min}$ is the minimum green time of phase j, s;

By referring to German guidelines for traffic signals [11], the minimum green times of the through phase and the left-turn phase are set as 15 and 10 s, respectively.

1.2.3 Early green module

If a bus of phase h approaches the intersection during the red phase and the light does not turn to green before it joins the queue, an early green request will be placed. The bus will be added to priority queue and its priority request will be held until it becomes the one with the highest priority level. Once priority is granted to it, the green time of the phase(s) between the current green phase i and phase h (including phase i when no green extension is placed on it) will be truncated so that the bus can clear the intersection earlier. The necessary green time of each phase can be obtained by Eq. (4), which can reduce the negative impacts on the general traffic to some extent.

From the above description we can find that when the saturation degrees of all the phases are larger than 0.95, the early green module will not be suitable for application because no marginal green time can be truncated.

2 Simulation Experiment and Results

2.1 Simulation environment

The proposed algorithm is applied to a signalized intersection in the VISSIM environment to test its performance. Fig. 3 illustrates the intersection structure and its phase diagram that are modeled to conduct the experiments. The intersection has four lags and four signal phases. Two group detectors are placed. One group is bus detectors to detect the presence of buses and the other group is inductive loop detectors to detect the traffic volume.

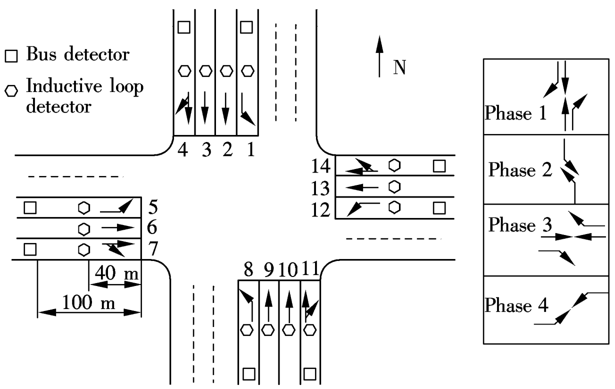

Fig. 3 Sketch and phase diagram of the studied intersection

To evaluate the potential benefits of the MPBSP algorithm, two algorithms are simulated:

1) The base algorithm is a normal timing scheme that does not provide a priority to a bus. The signal controller runs normal timing schemes obtained by Webster's timing method[12].

2) The MPBSP algorithm provides priority to buses which arrive at 1 phase, 2 phases, 3 phases and 4 phases, respectively.

The total lost green time of the simulated intersection is 12 s. The minimum green times of phase 1 and phase 3 are set as 15 s and those of phase 2 and phase 4 are set as 10 s. Each bus equals 3 unit cars in size. In the VISSIM environment, the saturation flow rate is calibrated carefully and the value of each lane is 2 100 pcu/h.

The simulation analysis focuses on the evaluation of the capability of the two algorithms to cope with changing traffic flows under different demand levels. Four different demand levels of the intersection are simulated. The average volume to capacity ratios (v/c) of the four demand levels are 0.6, 0.7, 0.8 and 0.9, respectively. Initial timing parameters and total volumes are shown in Tab. 1. Total volume is the sum of volumes of four critical lanes. The lanes that belong to the same signal phase have the the same traffic volume. According to the green time allocation principle, the four phases have the same saturation degree.

Tab. 1 Initial signal timing parameters of the simulated intersection

v/c	Cycle length/s	Green time/s				Total volume/ (pcu · h^{-1})
		Phase 1	Phase 2	Phase 3	Phase 4	
0.6	90	26	13	26	13	1 092
0.7	100	29	15	29	15	1 294
0.8	110	33	16	33	16	1 497
0.9	120	36	18	36	18	1 701

Buses arrive at the intersection from eight lanes. By referring to the bus volumes of intersections that are located in the central area of Changchun, China, the bus volume of each lane is set in the range of 5 to 40 veh/h. Bus demand is divided into three levels, and the volumes are shown in Tab. 2. According to the investigated data, the bus volumes of the protected left phases are smaller than those of the through phases.

Tab. 2 Bus demand of each lane under different levels veh/h

Bus volume	Lane 10	Lane 3	Lane 13	Lane 6	Lane 8	Lane 1
Low demand	10	10	10	10	5	5
Medium demand	25	25	25	25	10	10
High demand	40	40	40	40	15	15

To study the impact of the number of priority phases on control benefits, two-phase BSP, three-phase BSP and four-phase BSP schemes are simulated to study the relationships. The single-phase BSP(SPBSP) scheme is also simulated and it is compared with the MPBSP to evaluate the effectiveness of the MPBSP. Because the BSP is usually given to the phases that have high bus frequencies, so phase 1 is selected as the priority phase when implementing single-phase BSP. Priority phases and corresponding bus arrival lanes are shown in Tab. 3.

Tab. 3 Priority phase and corresponding lanes

Number of priority phases	Priority phases	Corresponding lanes
1	Phase 1	Lane 4, 11
2	Phase 1, 3	Lane 4, 11, 7, 14
3	Phase 1, 2, 3	Lane 4, 11, 7, 14, 1, 8
4	Phase 1, 2, 3, 4	Lane 4, 11, 7, 14, 1, 8, 5, 12

2.2 Experimental results and analysis

Three indices are used to test the algorithm performance. These indices include: 1) Average delay of buses that arrive on eight lanes (ADB); 2) Average delay of vehicles that arrive on four critical lanes (ADV); 3) Average delay of vehicles that arrive on critical lanes of non-priority phases (ADVN).

The statistical results of the evaluation indices of the two algorithms are obtained. The results indicate that the provisions of the BSP are generally beneficial to buses in all the scenarios. Compared with the base algorithm, the MPBSP can result in the reduction in ADB and the increase in ADV and ADVN to some extent. To obtain the optimal application environment of the MPBSP algorithm, it is necessary to analyze the impacts of different factors on evaluation indices.

2.2.1 Impact of number of priority phases

The SPBSP strategy can reduce the bus delays of phase 1 significantly and lead to a reduction of ADB. With the increase in priority phases, an increasing tendency in ADB reduction is generated, which indicates that the MPBSP strategy is more beneficial to buses than the SPBSP strategy.

Tab. 4 illustrates the variations of ADB and ADV as a function of the number of priority phases for low bus demand level and an intersection v/c ratio of 0.6. It shows that as the number of priority phases increases, the ADB shows a reduction tendency. This is because more buses can receive priority when the MPBSP strategy is applied. However, the reduction ranges of ADB decrease as the number of priority phases increases. This can be mainly attributed to the fact that there is limited green time for each phase for a green extension or a red truncation due to the conditional priority strategy. Average green time allocated to each bus for priority will decrease with the increase in buses that are granted priority.

Tab. 4 Impact of number of priority phases on ADB and ADV

Number of priority phases	ADB/s	ADV/s
0	27.4	31.8
1	25.7	32.3
2	24.8	32.5
3	24.5	32.1
4	24.1	32.1

Tab. 4 also demonstrates that with the increase in priority phases, there is not a significant change in ADV. There may be two reasons accounting for this phenomenon: 1) The conditional priority strategy (saturation degree limitation) limits the increase in negative impacts caused by buses; 2) When a bus is granted priority, some general vehicles that belong to the same phase as the bus can also clear the intersection, which reduces the average delay of general traffic.

Tab. 5 shows the changing tendency of ADVN. With the increase in priority phases, the negative impact on non-priority phase(s) increases significantly. This is because more buses place requests with the increase in priority phases, and thus red truncation is adopted frequently and the green times of non-priority phases have to be truncated. Especially for phase 4, when the three-phase BSP scheme is applied, its marginal green times are requested during the other three phases, which results in a significant increase in its average vehicle delay.

Tab. 5 Impact of number of priority phases on AVDN

Number of priority phases	Algorithms	Phase 2	Phase 3	Phase 4
1	Base algorithm	36.5	23.9	35.9
	MPBSP	38.1	24.6	39.9
2	Base algorithm	37.4		37.0
	MPBSP	39.6		41.0
3	Base algorithm			36.4
	MPBSP			45.5

In other scenarios, the impacts of priority phases on ADB, ADV and AVDN are similar to those shown in Tabs. 4 and 5.

2.2.2 Impact of bus demand

Bus demand is one of the important factors that may affect control benefits, as more arrival buses mean more priority requests. Tab. 6 displays the variations of ADB and ADV for a four-phase BSP scheme and an intersection v/c ratio of 0.7. Improvements of ADB show a decrease tendency as bus demand increases from a low level to a high level. For example, when the bus demand is low, compared with the base algorithm, the MPBSP algorithm can result in a reduction of 11.4% in ADB; however, when the bus demand is high, the value decreases to 7.9%. The changing tendency of ADV is the opposite; the negative impacts on ADV increase from 1.7% to 3.7%.

Tab. 6 Impact of bus demand on ADB and ADV %

Bus demand	Improvement of ADB	Improvement of ADV
Low	11.4	−1.7
Medium	10.2	−3.1
High	7.9	−3.7

As described before, there are limited green times for bus priority due to the conditional priority strategy, and thus the number of buses that can be granted priority is also limited. The increase in arrival buses will result in a reduction in the percent of buses that are granted priority. So the improvement range of ADB decreases as bus demand increases. Furthermore, with the number of buses granted priority increases, green extension and red truncation will be applied more frequently, which results in the increase in ADV. The ADVN also shows the same tendency as ADV.

2.2.3 Impact of volume to capacity ratios

Tab. 7 displays the variations of ADB and ADV for a three-phase BSP scheme in low bus demand scenarios. As the v/c ratios increase from 0.6 to 0.9, the improvement of ADB decreases from 10.5% to 7.7%. However, the negative impact on ADV increases from 0.9% to 6.3%. From Tabs. 6 and 7, we can find that the v/c ratios and bus demands have similar impacts on evaluation indices.

Tab. 7 Impact of v/c ratios on ADB and ADV %

v/c ratio	Improvement of ADB	Improvement of ADV
0.6	10.5	−0.9
0.7	9.3	−2.5
0.8	8.9	−4.7
0.9	7.7	−6.3

3 Conclusions

1) The MPBSP strategy outperforms the SPBSP strategy in reducing bus delays, and with the increase in priority phases, the reduction percentages of bus delays also increase.

2) The MPBSP strategy established in this paper is a conditional strategy. Green duration adjustments of all phases are limited by a threshold value of 0.95. Therefore, an early green strategy, which is the most frequently requested by buses, can make sense only when the saturation degree of at least one non-priority phase is smaller than 0.95.

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一种单点多相公交信号优先控制策略

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摘要:为满足交叉口短时间内多个方向有公交车到达时的信号优先需求,提出了一种单点多相公交信号优先策略. 针对不同相位公交优先申请间的冲突,提出了“就近原则”以合理安排各公交车的优先级别并确定最佳优先顺序. 为避免出现过饱和现象,提出了一种有限优先策略,即在各相位饱和度不超过 0. 95 的情况下,采用绿灯延长、绿灯提前启亮给予具有最高优先级别的公交车信号优先. 在 VISSIM 中验证了所提算法的有效性,并与普通信号配时进行对比;分析了优先相位数、公交需求、交叉口流量比等因素对算法效益的影响. 结果表明:多相公交信号优先算法能有效降低公交车延误,且随着优先相位数的增加,交叉口公交车延误降低幅度越大.

关键词:公交信号优先;多相位;绿灯提前启亮;绿灯延长;孤立交叉口
中图分类号:U491