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Method of the left-turning bus priority at intersections based on a variable lane

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Abstract: To reduce the delay of left-turning buses and improve the traffic efficiency at signalized intersections, a novel variable bus approach lane (VBAL) control method based on bus pre-signals is proposed. This method combines the variable lane with the bus priority pre-signal, and realizes the left-turning bus priority without causing great impact on other vehicles. To validate the effectiveness of the method, the VBAL scheme was compared with the single left-turn lane scheme (SLTL) and the double left-turn lane scheme (DLTL). On this basis, the delay change calculation model of left-turning buses and through vehicles were established by the cumulative curve graphic method. The influence of vehicle proportion and green split on the model was studied through sensitivity analysis. The results show that VBAL can reduce the delay of left-turning bus and the increase of through vehicle delay to the greatest extent. Finally, the scheme was applied to a real-world intersection, and the results demonstrate the effectiveness and advantage of the VBAL scheme.

Key words: traffic engineering; bus priority; dynamic lane; pre-signal; cumulative curve

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Bus signal priority is of great significance to improving bus operating efficiency. Current priority methods seldom consider left turns; however, some problems cannot be ignored for left-turning buses. When a bus stop is located upstream of an intersection, left-turning buses stopping at the station always experience difficulties in maneuvering to inner left-turn lanes. More specifically, an upstream bus stop is located in a curb lane, and buses have to merge across multiple lanes to reach a left-turn bay. To solve the merging problem, approaches can be considered, including constructing double left-turn lanes (DLTLs) at intersections. However, left-turning buses still suffer from the difficulty of merging into queuing left-turning cars, which often queue upstream of bus stops during peak hours. To solve this problem, setting up a dedicated bus lane (DBL) for left-turning buses can be considered. In addition, pre-signals can be applied to provide priorities for left-turning buses.

In the present study, transit signal priority (TSP), DBLs, and intermittent bus lanes (IBLs) have been used to provide bus priorities. By adjusting traffic signal plans based on bus arrivals, the delay of buses can be reduced[1]. A DBL can be combined with TSP to improve its advantage, but it is only suitable for light volumes of cars because it removes one lane from conventional lanes[2]. Viegas et al. [3] proposed the use of IBLs, where cars are forbidden to use lanes downstream of advancing buses. However, when there is no bus arriving, cars using such lanes could increase discharges from the arterial[4].

In addition, as a common bus priority method, pre-signals have been widely used in urban road intersections. There are two types of pre-signals: whole pre-signal and local pre-signal. In a whole pre-signal, all lanes should be set with a pre-signal. To accurately evaluate a whole pre-signal, He et al. [5] proved that bus priorities with pre-signals could improve the intersection capacity. Follow-up studies gradually focused on the control model optimization of pre-signals and the solution method of related parameters[6-10]. To meet the diverse traffic demand of intersections, local pre-signals were proposed. In local pre-signals, only one or several lanes are set with pre-signals. In this case, bus priorities can be provided without affecting other movements. A local pre-signal is usually combined with a complex, unconventional design, such as a contraflow left-turn design[11].

However, the two methods will increase the delay of non-priority vehicles and cause waste of space resources at intersections when the proportion of left-turning buses is low. Hence, in this study, a left-turning bus lane is set upstream of the adjacent lane of a left-turn lane, which is controlled by a pre-signal. The downstream of the pre-signal is a variable lane in which buses and non-priority vehicles are allowed to travel simultaneously. The aforementioned approach can save the lane-changing time for left-turning buses. Moreover, the non-priority through vehicles can enter the variable lane, which would minimize the increased delay of non-priority vehicles.

1 Design Concept of VBAL

The intersection implementing the variable bus ap-

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proach lane (VBAL) scheme shall meet the following conditions:

1) There shall be at least three or more lanes at the approach.

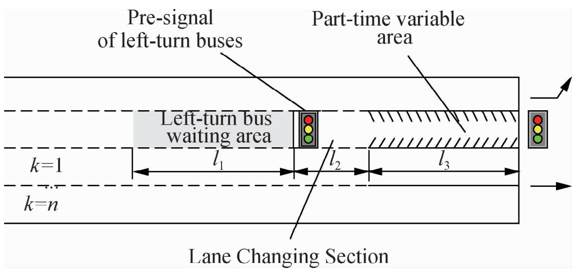
2) A sufficient distance shall be reserved between the stop line and the upstream bus stop.

3) The saturation of the intersection should be less than 0.9.

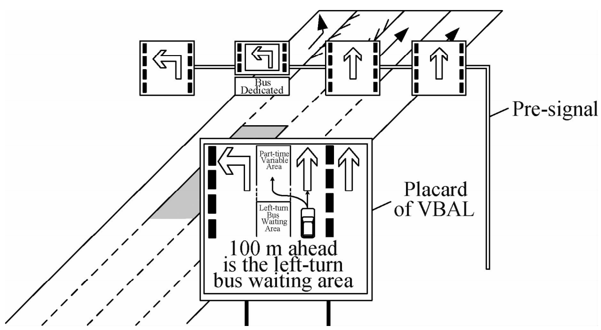
4) There should be a relatively stable number of left-turning buses arriving in each cycle.

1.1 Geometric and phase design

The geometric design of the VBAL is shown in Fig. 1(a), while a reference design for a pre-signal and placard is shown in Fig. 1(b). The variable lane is located in the zigzag marking section, which can be used by through vehicles and left-turning buses at different times. The shadow area upstream is a dedicated waiting area for left-turning buses. The section between the two areas is a lane-changing section for non-priority vehicles.



(a)



(b)

Fig. 1 Layout of the VBAL. (a) Geometric design; (b) Reference design for a pre-signal and placard

Three common phases, namely, four-step phase, single-approach-released-in-turn (SARIT) phase, and overlapping phase, will be discussed in this section. For the convenience of description, traffic methods are explained as follows in the case of the main signal being red, through green, left-turn green, and through-left green.

1) Queue distribution. Left-turning cars wait in the left-turn lane. Left-turning buses queue on the bus lane, and through vehicles wait on the variable or through lanes (see Fig. 2(a)).

2) The main signal is through green. In stage 1, the through vehicles pass the intersection from a variable lane or through lanes. Left-turning cars and buses queue up on the left-turn lane and waiting area, respectively (see Fig. 2(b)). In stage 2, waiting left-turning buses are allowed to enter the variable lane ahead of time (see Fig. 2(c)).

3) The main signal is left-turn green. In stage 1, left-turning buses and cars would be released (see Fig. 2(d)). In stage 2, after all the waiting left-turning buses are released, left-turning cars are allowed to enter the inner left-turn lane or variable area (see Fig. 2(e)).

4) The main signal is through-left green. In stage 1, left-turning buses pass the intersection through a variable area (see Fig. 2(f)). In stage 2, through and left-turning vehicles could be allowed to use the variable area to pass the intersection (see Fig. 2(g)).

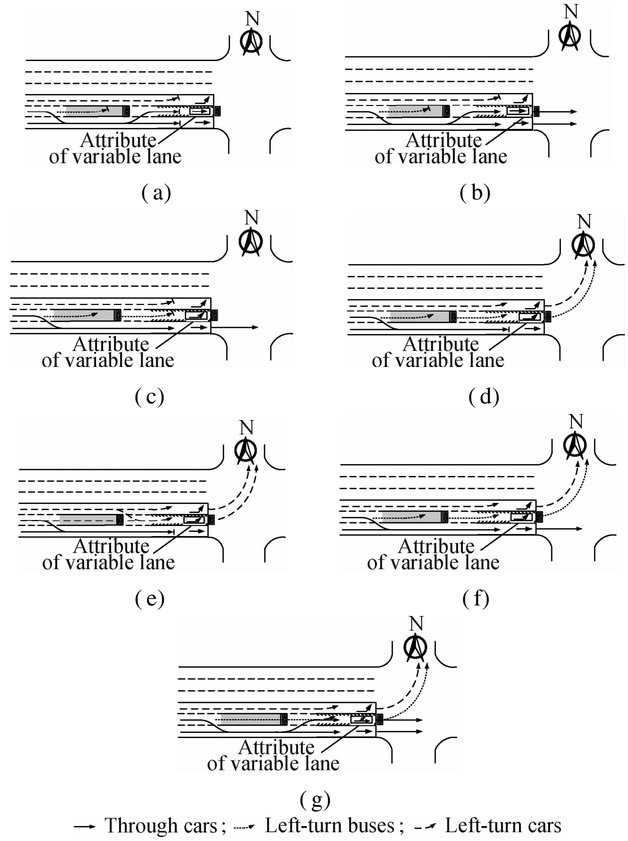


Fig. 2 Traffic method of the VBAL scheme under different main signals. (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4; (e) Case 5; (f) Case 6; (g) Case 7

As discussed above, the traffic methods under the three phases can be obtained by recombining the above situations. In the four-step phase, the release process of the vehicle is (a)→(b)→(c)→(d)→(e). In the case of SARIT, the process is (a)→(f)→(g). In the overlapping phase, the process is (a)→(b)→(f)→(g) (see Tab. 1). In addition, the pre-signal cannot turn green in advance in the SARIT phase because through vehicles would queue on the variable lane, which leads to the loss of priority for left-turning buses. Therefore, whether the

SARIT phase can be applied to provide priorities for left-turning buses has great uncertainties.

Tab. 1 Steps for vehicle release in the VBAL scheme under different phases

Phase	Steps for vehicles released
Four-step phase	(a)→(b)→(c)→(d)→(e)
SARIT	(a)→(f)→(g)
Overlapping phase	(a)→(b)→(f)→(g)

1.2 Calculation model of control parameters

The green time of a pre-signal consists of the green time starting in advance g_1 and green duration g_3. Left-turning buses can reach the stop line of the main signal within g_1, and the stranding phenomenon is also avoided.

$$g_1 = \left[\frac{l_2 + l_3}{v} + L\right] \tag{1}$$

$$g_3 = g_2 - g_1 \tag{2}$$

where l_3 and l_2 denote the length of the variable lane and lane changing section, m, respectively; v is the average speed of buses, m/s; L is the lost time of vehicle starting, s; and g_2 is the left-turn green time of the main signal, s.

The geometric parameters of the VBAL depend on l_1, l_2, and l_3, where l_3 is equal to the approach lanes, and l_1 should meet the maximum queuing distance required for left-turning buses. Suppose that the number of left-turning buses arriving and departing in each signal period is a and b, respectively. Then, the probability of α left-turning buses queuing in the waiting area, P_α, can be given by[12]

$$P_\alpha = \left(1 - \frac{a}{b}\right)\left(\frac{a}{b}\right)^\alpha \tag{3}$$

The maximum number of queuing buses M can be obtained by

$$M = \frac{\ln\left(1 - 1 - \left(\frac{a}{b}\right)^{M+1}\right)}{\ln\left(\frac{a}{b}\right)} - 1 \tag{4}$$

l_1 and l_2 are given by [12]

$$l_1 = Ml_\mathrm{b} + (M-1)\,l \tag{5}$$

$$l_2 = \int_0^1 v(\tau)\cos\theta_\mathrm{d}(\tau)\,\mathrm{d}\tau \tag{6}$$

where l_b denotes the average length of buses, m; l represents the safe stopping distance of buses, m; v is the speed of cars, m/s; and θ_d is the desired heading angle of cars.

2 Person-Based Delay Model

2.1 Four-phase

Fig. 3 presents the cumulative curves under the VBAL and SLTL schemes. As shown in Fig. 3(a), the average reduction of the left-turning bus delay under the VBAL scheme, D_b^F, can be calculated as

$$D_\mathrm{b}^\mathrm{F} = \frac{d_\mathrm{b}^\mathrm{F}}{q_\mathrm{b}(T)} \tag{7}$$

$$d_\mathrm{b}^\mathrm{F} = \begin{cases} \int_{t_\mathrm{A}^\mathrm{b}}^{t_\mathrm{B}^\mathrm{b}} S_\mathrm{b}(t)\,\mathrm{d}t + \int_{t_\mathrm{B}^\mathrm{b}}^{t_\mathrm{D}^\mathrm{b}} q_\mathrm{b}(t)\,\mathrm{d}t + \int_{t_\mathrm{D}^\mathrm{b}}^{t_\mathrm{C}^\mathrm{b}} q_\mathrm{b}(t) - S_\mathrm{L}(t)\,\mathrm{d}t & t_\mathrm{B} < t_\mathrm{D} \\ \int_{t_\mathrm{A}^\mathrm{b}}^{t_\mathrm{D}^\mathrm{b}} S_\mathrm{b}(t)\,\mathrm{d}t + \int_{t_\mathrm{D}^\mathrm{b}}^{t_\mathrm{B}^\mathrm{b}} q_\mathrm{b}(t)\,\mathrm{d}t + \int_{t_\mathrm{B}^\mathrm{b}}^{t_\mathrm{C}^\mathrm{b}} q_\mathrm{b}(t) - S_\mathrm{L}(t)\,\mathrm{d}t & t_\mathrm{B} \geqslant t_\mathrm{D} \end{cases} \tag{8}$$

where d_b^F denotes the delay reduction of left-turning buses, s; $S_\mathrm{b}(t)$ and $S_\mathrm{L}(t)$ are the saturation flow rates of a bus lane and left-turn lanes, pcu/h, respectively; $q_\mathrm{b}(t)$ is the arrival rate of left-turning buses, pcu/h; t_A^b is equivalent to R_L^F, which is the red time for the left-turn of the main signal, s; t_B^b and t_C^b denote the time from the beginning of a cycle to the departure time of all queuing left-turning buses, s, respectively; $t_\mathrm{D}^\mathrm{b} = R_\mathrm{L}^\mathrm{F} + g$, and g is the green time of the pre-signal starting in advance, s. As shown in Fig. 3(b), the average increase in delay under the VBAL scheme, D_T^F, can be calculated as

$$D_\mathrm{T}^\mathrm{F} = \frac{d_\mathrm{T}^\mathrm{F}}{q_\mathrm{T}(T)} \tag{9}$$

$$d_\mathrm{T}^\mathrm{F} = \int_{t_\mathrm{D}^\mathrm{T}}^{t_\mathrm{B}^\mathrm{T}} [nS_\mathrm{T}(t) - (n-1)S_\mathrm{T}(t)]\,\mathrm{d}t + \int_{t_\mathrm{B}^\mathrm{T}}^{t_\mathrm{C}^\mathrm{T}} [q_\mathrm{T}(t) - (n-1)S_\mathrm{T}(t)]\,\mathrm{d}t \tag{10}$$

where d_T^F is the increased delay of through vehicles, s; $S_\mathrm{T}(t)$ is the saturation flow rate of the through lane, pcu/h; $q_\mathrm{T}(t)$ the arrival rate of through vehicles, pcu/h; t_B^T and t_C^T represent the time from the beginning of a cycle to the departure time of all queuing through vehicles under the two schemes, s, respectively; t_D^T is the intermediate variable. As shown in Fig. 3(c), the average delay reduction of left-turning cars under the VBAL scheme, D_L^F, can be given by

$$D_\mathrm{L}^\mathrm{F} = \frac{d_\mathrm{L}^\mathrm{F}}{q_\mathrm{L}(T)} \tag{11}$$

$$d_\mathrm{L}^\mathrm{F} = \int_{t_\mathrm{A}^\mathrm{L}}^{t_\mathrm{B}^\mathrm{L}} (m+1)S_\mathrm{L}(t) - mS_\mathrm{L}(t)\,\mathrm{d}t + \int_{t_\mathrm{B}^\mathrm{L}}^{t_\mathrm{C}^\mathrm{L}} q_\mathrm{L}(t) - mS_\mathrm{L}(t)\,\mathrm{d}t \tag{12}$$

where d_L^F is the delay reduction of left-turning cars, s; $S_\mathrm{L}(t)$ is the saturation flow rate of the left-turn lane, pcu/h; $q_\mathrm{L}(t)$ is the arrival rate of left-turning cars, pcu/h, $t_\mathrm{A}^\mathrm{L} = R_\mathrm{L}^\mathrm{F}$; t_B^L and t_C^L denote the time from the beginning of a cycle to the departure time of all queuing left-turning cars, s, respectively; m is the number of left-turn lanes.

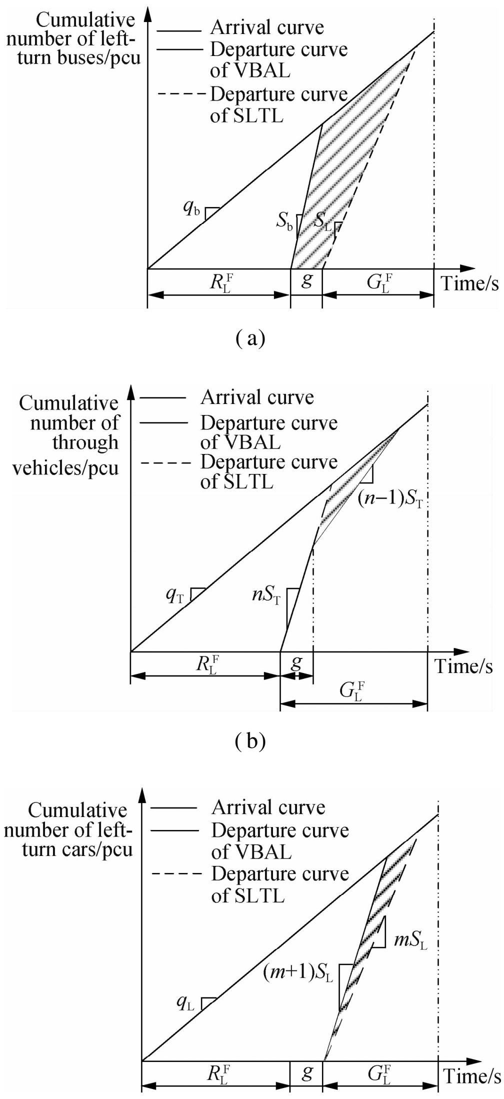


Fig. 3 Comparison of delays between the VBAL and SLTL schemes. (a) Left-turning buses; (b) Through vehicles; (c) Left-turning cars

Fig. 4 presents the cumulative curves under the DLTL and SLTL schemes. The delay variation of left-turning buses is shown in Fig. 4(a). The average delay reduction of left-turning buses under the DLTL scheme, $D_b^{F'}$, is given by

$$D_b^{F'} = \frac{d_b^{F'}}{q_b(T)} \tag{13}$$

$$d_b^{F'} = \int_{t_A^{b'}}^{t_B^{b'}} 2S_L(t) - S_L(t)\,dt + \int_{t_B^{b'}}^{t_C^{b'}} q_b(t) - S_L(t)\,dt \tag{14}$$

where $d_b^{F'}$ is the delay reduction of left-turning buses, s; $t_B^{b'}$ and $t_C^{b'}$ are the time from the beginning of the cycle to the departure time of all queuing left-turning buses in a cycle under the two schemes, s, respectively. As shown in Fig. 4(b), the average delay increases in through vehicles after setting the DLTL scheme, $D_T^{F'}$, is given by

$$D_T^{F'} = \frac{d'_T}{q_T(T)} \tag{15}$$

$$d'_T = \int_{t_A^T}^{t_B^T} nS_T(t) - (n-1)S_T(t)\,dt + \int_{t_B^T}^{t_C^T} q'_T(t) - (n-1)S_T(t)\,dt \tag{16}$$

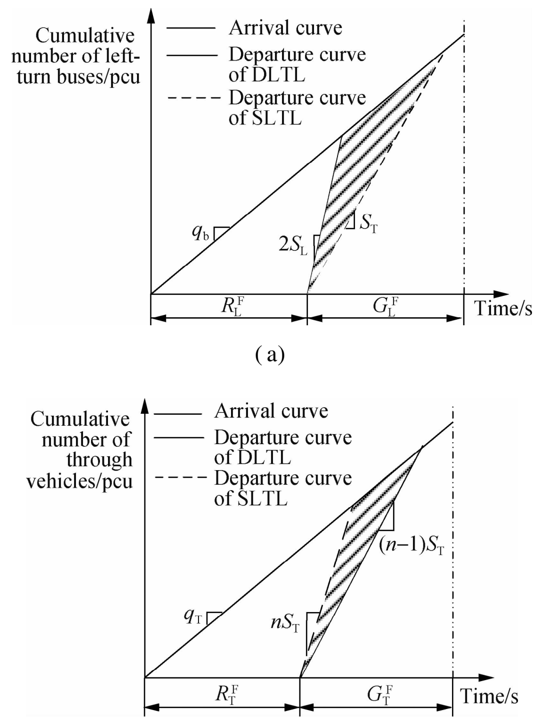


Fig. 4 Comparison of delays between the DLTL and SLTL schemes. (a) Left-turning buses; (b) Through vehicles

The average variation of delays can be calculated as

$$D_{VBAL}^F = \frac{-D_b^F p_b o_b + D_T^F p_T o_c - D_L^F p_L o_c}{p_b o_b + (p_T + p_L) o_c} \tag{17}$$

$$D_{DLTL}^F = \frac{-D_b^{F'} p_b o_b + D_T^{F'} p_T o_c}{p_b o_b + p_T o_c} \tag{18}$$

where p_b, p_T, and p_L are the proportions of left-turning buses, through vehicles, and left-turning cars arriving at the intersection in a cycle, respectively; o_b and o_c are the average number of passengers carried by buses and cars, respectively.

2.2 Overlapping phase

Fig. 5 shows the cumulative curve of vehicles under the VBAL and SLTL schemes. As shown in Fig. 5(a), the average reduction delay of left-turning buses in the VBAL, D_b^O, can be calculated as follows:

$$D_b^O = \frac{d_b^O}{q_b(T)} \tag{19}$$

$$d_{\mathrm{b}}^{\mathrm{O}} = \begin{cases} \int_{t_{\mathrm{A}}^{\mathrm{b}'}}^{t_{\mathrm{B}}^{\mathrm{b}}} S_{\mathrm{b}}(t)\,\mathrm{d}t + \int_{t_{\mathrm{B}}^{\mathrm{b}}}^{t_{\mathrm{D}}^{\mathrm{b}'}} q_{\mathrm{b}}(t)\,\mathrm{d}t + \int_{t_{\mathrm{D}}^{\mathrm{b}'}}^{t_{\mathrm{C}}^{\mathrm{b}}} q_{\mathrm{b}}(t) - S_{\mathrm{L}}(t)\,\mathrm{d}t & t_{\mathrm{B}}^{\mathrm{b}} < t_{\mathrm{D}}^{\mathrm{b}'} \\ \int_{t_{\mathrm{A}}^{\mathrm{b}'}}^{t_{\mathrm{D}}^{\mathrm{b}'}} S_{\mathrm{b}}(t)\,\mathrm{d}t + \int_{t_{\mathrm{D}}^{\mathrm{b}'}}^{t_{\mathrm{B}}^{\mathrm{b}}} q_{\mathrm{b}}(t)\,\mathrm{d}t + \int_{t_{\mathrm{B}}^{\mathrm{b}}}^{t_{\mathrm{C}}^{\mathrm{b}}} q_{\mathrm{b}}(t) - S_{\mathrm{L}}(t)\,\mathrm{d}t & t_{\mathrm{B}}^{\mathrm{b}} \geqslant t_{\mathrm{D}}^{\mathrm{b}'} \end{cases} \tag{20}$$

where $d_{\mathrm{b}}^{\mathrm{O}}$ denotes the delay reduction of left-turning buses, s. $t_{\mathrm{A}}^{\mathrm{b}'} = R^{\mathrm{O}} + r$, R^{O} is the red time of the main signal, s. r is the red time of the pre-signal when the main signal shows through green, s. $t_{\mathrm{D}}^{\mathrm{b}'} = R^{\mathrm{O}} + r + g$.

As shown in Fig. 5(b), the delay of through vehicles is increased after the implementation of the VBAL scheme. The average increase in delay, $D_{\mathrm{T}}^{\mathrm{O}}$, can be given by

$$D_{\mathrm{T}}^{\mathrm{O}} = \frac{d_{\mathrm{T}}^{\mathrm{O}}}{q_{\mathrm{T}}(T)} \tag{21}$$

where $d_{\mathrm{T}}^{\mathrm{O}}$ is the delay increase of through vehicles, s.

$$d_{\mathrm{T}}^{\mathrm{O}} = \begin{cases} \int_{t_{\mathrm{E}}^{\mathrm{T}}}^{t_{\mathrm{B}}^{\mathrm{T}}} nS_{\mathrm{T}_1}(t) - (n-1)S_{\mathrm{T}_1}(t)\,\mathrm{d}t + \int_{t_{\mathrm{B}}^{\mathrm{T}}}^{t_{\mathrm{F}}^{\mathrm{T}}} q_{\mathrm{T}}(t) - (n-1)S_{\mathrm{T}_1}(t)\,\mathrm{d}t + \int_{t_{\mathrm{F}}^{\mathrm{T}}}^{t_{\mathrm{C}}^{\mathrm{T}}} q_{\mathrm{T}}(t) - nS_{\mathrm{T}_2}(t)\,\mathrm{d}t & t_{\mathrm{B}}^{\mathrm{T}} < t_{\mathrm{F}}^{\mathrm{T}} \\ \int_{t_{\mathrm{E}}^{\mathrm{T}}}^{t_{\mathrm{F}}^{\mathrm{T}}} nS_{\mathrm{T}_1}(t) - (n-1)S_{\mathrm{T}_1}(t)\,\mathrm{d}t + \int_{t_{\mathrm{F}}^{\mathrm{T}}}^{t_{\mathrm{B}}^{\mathrm{T}}} nS_{\mathrm{T}_1}(t) - (n-1)S_{\mathrm{T}_2}(t)\,\mathrm{d}t + \int_{t_{\mathrm{B}}^{\mathrm{T}}}^{t_{\mathrm{C}}^{\mathrm{T}}} q_{\mathrm{T}}(t) - nS_{\mathrm{T}_2}(t)\,\mathrm{d}t & t_{\mathrm{B}}^{\mathrm{T}} \geqslant t_{\mathrm{F}}^{\mathrm{T}} \end{cases} \tag{22}$$

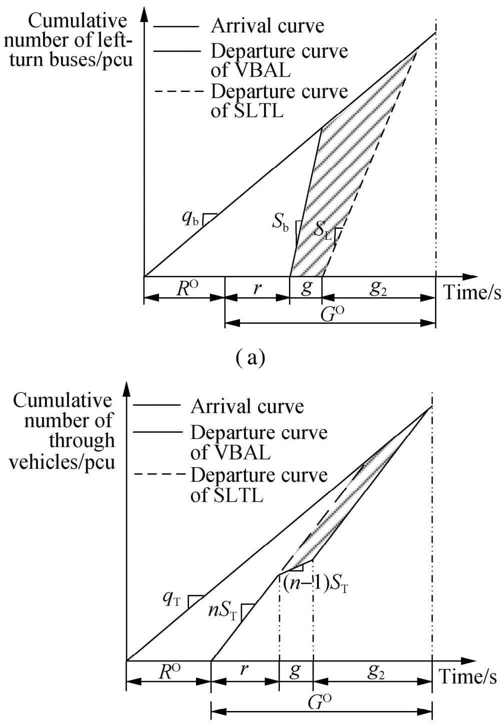


Fig. 5 Comparison of delays between the VBAL and SLTL schemes. (a) Left-turning buses; (b) Through vehicles

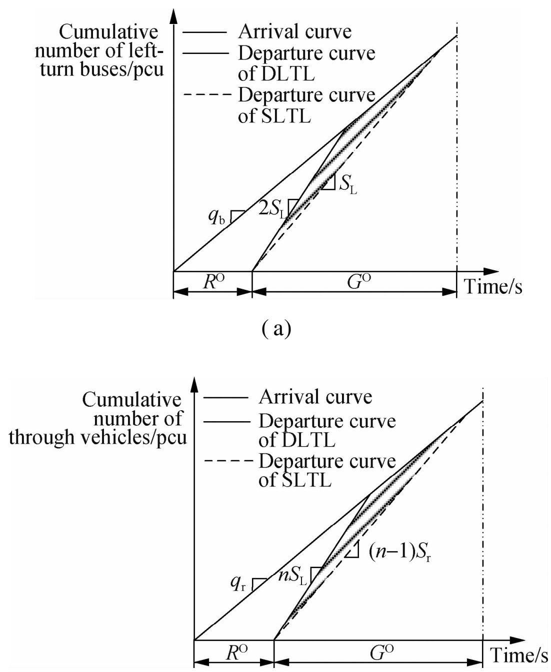


Fig. 6 Comparison of delays between the DLTL and SLTL schemes. (a) Left-turning buses; (b) Through vehicles

The cumulative curves of the DLTL and SLTL schemes are illustrated in Fig. 6. As shown in Fig. 6(a), the average reduction of the left-turning bus delay under the DLTL scheme, $D_{\mathrm{b}}^{\mathrm{O}'}$, is given by

$$D_{\mathrm{b}}^{\mathrm{O}'} = \frac{d_{\mathrm{b}}^{\mathrm{O}'}}{q_{\mathrm{b}}(T)} \tag{23}$$

$$d_{\mathrm{b}}^{\mathrm{O}'} = \int_{t_{\mathrm{A}}^{\mathrm{b}}}^{t_{\mathrm{B}}^{\mathrm{b}}} 2S_{\mathrm{L}}(t) - S_{\mathrm{L}}(t)\,\mathrm{d}t + \int_{t_{\mathrm{B}}^{\mathrm{b}}}^{t_{\mathrm{C}}^{\mathrm{b}}} q_{\mathrm{b}}(t) - S_{\mathrm{L}}(t)\,\mathrm{d}t \tag{24}$$

where $d_{\mathrm{b}}^{\mathrm{O}'}$ is the delay reduction of left-turning buses, s. $t_{\mathrm{A}}^{\mathrm{b}} = R^{\mathrm{O}}$.

As shown in Fig. 6(b), the average increase in the through-vehicle delay under the DLTL scheme, $D_{\mathrm{T}}^{\mathrm{O}'}$, is

$$D_{\mathrm{T}}^{\mathrm{O}'} = \frac{d_{\mathrm{T}}^{\mathrm{O}'}}{q_{\mathrm{T}}(T)} \tag{25}$$

$$d^{\mathrm{O}'}{}_{\mathrm{T}} = \int_{t_{\mathrm{A}}^{\mathrm{T}}}^{t^{\mathrm{T}}{}_{\mathrm{B}}} nS_{\mathrm{T}}(t) - (n-1)S_{\mathrm{T}}(t)\,\mathrm{d}t + \int_{t_{\mathrm{B}}^{\mathrm{T}}}^{t_{\mathrm{C}}^{\mathrm{T}}} q_{\mathrm{T}}(t) - (n-1)S_{\mathrm{T}}(t)\,\mathrm{d}t \tag{26}$$

where $d_{\mathrm{T}}^{\mathrm{O}'}$ is the increase in delay for through vehicles, s.

The average delay variation of the schemes can be calculated as follows:

$$D_{\mathrm{VBAL}}^{\mathrm{O}} = \frac{-D_{\mathrm{b}}^{\mathrm{O}} p_{\mathrm{b}} o_{\mathrm{b}} + D_{\mathrm{T}}^{\mathrm{O}} p_{\mathrm{T}} o_{\mathrm{c}}}{p_{\mathrm{b}} o_{\mathrm{b}} + p_{\mathrm{T}} o_{\mathrm{c}}} \tag{27}$$

$$D_{\mathrm{DLTL}}^{\mathrm{O}} = \frac{-D_{\mathrm{b}}^{\mathrm{O}'} p_{\mathrm{b}} o_{\mathrm{b}} + D_{\mathrm{T}}^{\mathrm{O}'} p_{\mathrm{T}} o_{\mathrm{c}}}{p_{\mathrm{b}} o_{\mathrm{b}} + p_{\mathrm{T}} o_{\mathrm{c}}} \tag{28}$$

3 Sensitivity Analysis

A sensitivity analysis was conducted using MATLAB (2017a) to analyze the impacts of the vehicle arrival rate, green split of the main signal, and proportion of vehicle types. Suppose the cycle length was 180 s. The saturation flow rates of left-turn lanes and through lanes were 0.3 and 0.6 veh/h, respectively. The saturation flow rate of left-turning bus lanes was 0.5 veh/h. The average passenger occupancy of cars and buses was 5 and 40 per/veh, respectively. The advance time of pre-signal was 9 s.

As shown in Fig. 7(a), the delay reduction of left-turning buses in the VBAL scheme is larger than that in the DLTL scheme. Moreover, the VBAL scheme with an overlapping phase has the largest reduction of left-turning bus delay. The greater the arrival rate of left-turning buses, the greater the delay reduction. As shown in Fig. 7(b), with the increase in green split, the reduction in the left-turning-bus delay gradually decreases. In the two phases, the reduction in the left-turning-bus delay in the VBAL is greater than that in the DLTL.

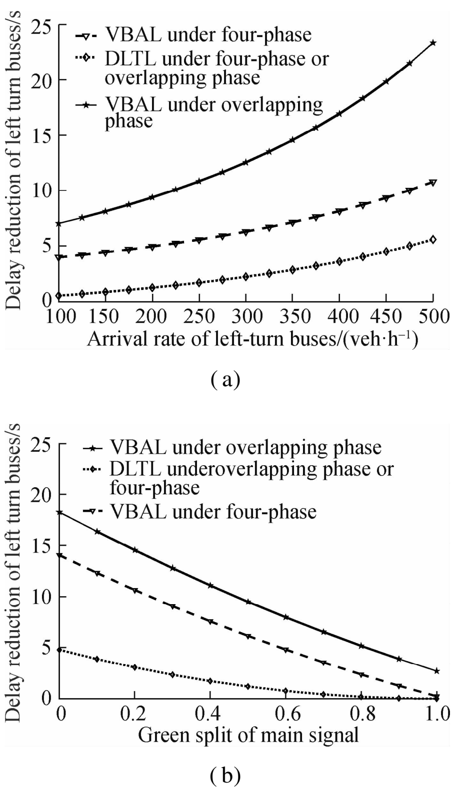


Fig. 7 Delay reduction of left-turning buses under different parameters. (a) Arrival rate; (b) Green split of main signals

As shown in Fig. 8(a), the delay increase of the VBAL scheme is the lowest under the overlapping phase, and the curve of the increase in delay tends to be flat with the increase in the arrival rate of through vehicles. While the arrival rate of through vehicles reaches approximately 3 000 veh/h, the increase in delay would significantly increase. As shown in Fig. 8(b), the increase in delay under the VBAL scheme is lower than that in the DLTL scheme. Clearly, the curve of the VBAL scheme gently changes around 0, which proves the implementation advantage of the VBAL scheme again.

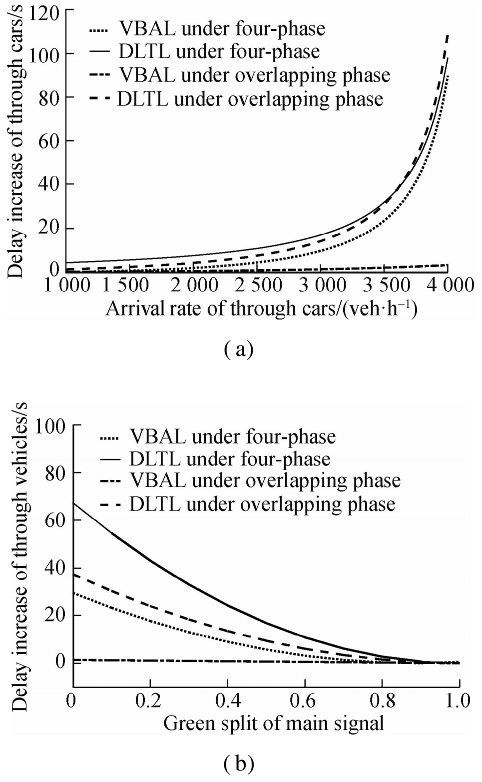


Fig. 8 Delay increase of through vehicles under different parameters. (a) Arrival rate; (b) Green split of the main signal

As shown in Fig. 9(a), the greater the proportion of left-turning buses, the greater the reduction of delay on the approach road. The DLTL scheme under the overlapping phase is not suitable for intersections because although its delay shows a downward trend, the variation of delay is always positive. In the other three schemes, the VBAL scheme with an overlapping phase has the largest delay reduction. As shown in Fig. 9(b), it has the opposite tendency as compared to that in Fig. 9(a). The VBAL scheme with an overlapping phase has the largest delay reduction.

4 Case Study

The effectiveness of the three schemes was evaluated at an intersection, i.e., the Furong-Xinyao Road located in Changsha. The traffic volume during the peak period is shown in Tab. 2. The overlapping phase was adopted in the north approach. Hence, the north approach was selected to evaluate the three schemes. Meanwhile, the signal timing of the VBAL scheme was obtained based on Eqs. (1) and (2), as shown in Fig. 10. According to Eqs. (3) to (6), l_3 and l_2 are 32 and 14 m, respectively.

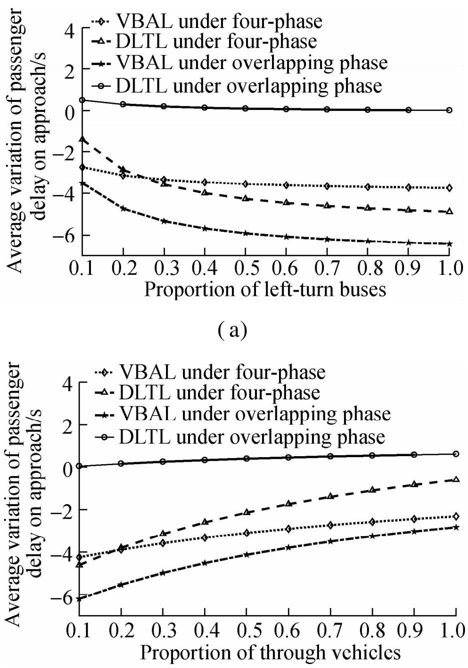


Fig. 9 Average variation of passenger delay on the approach under different proportions. (a) Left-turning buses; (b) Through vehicles

Tab. 2 Traffic flow at the intersection

Leg	Type	Traffic volume /(veh · h^{-1})		
		HT	LT	RT
East	Cars	214		811
	Buses	0		23
West	Cars	134	531	154
	Buses	0	28	3
South	Cars	1 938		132
	Buses	43		0
North	Cars	2 577	518	703
	Buses	55	27	23

Note: LT, HT, and RT refer to the left-turn, through, and right-turn movements, respectively.

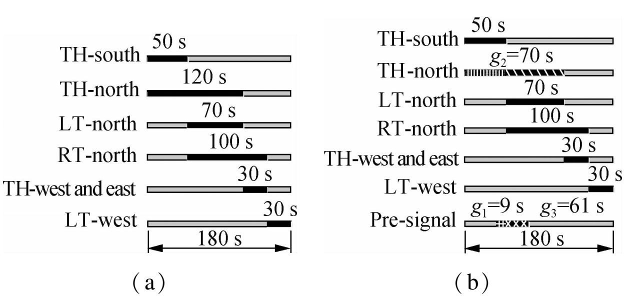


Fig. 10 Signal timing. (a) Before optimization (b) After optimization

We inputted the above data into the delay model, and the results are shown in Tab. 3. In the VBAL scheme, the delay of left-turning buses decreased by 5. 56 s, whereas in the DLTL scheme, it only decreased by 0. 05 s. For through vehicles, the delay of the DLTL and VBAL schemes increased by 8. 2 and 0. 85 s, respectively. Hence, the VBAL scheme can effectively reduce the delay of left-turning buses and minimize the increase in through-vehicle delay.

Tab. 3 Comparison of the average variations

Schemes	Vehicle type	Delay variation/s
VBAL	LT buses	−5. 56
	HT vehicles	0. 85
DLTL	LT buses	−0. 05
	HT vehicles	8. 20

To further verify the applicability of the method, VISSIM11. 0 was used to simulate the three schemes. As shown in Tab. 4, the delay reduction of left-turning buses is lower under the DLTL scheme than that under the VBAL scheme, whereas the delay of through vehicles was significantly increased. The queue length of the left-turn lane in the VBAL scheme was less than that of the DLTL scheme, but the queue length of through vehicles was slightly increased. Hence, the VBAL scheme is more suitable than the DLTL scheme.

Tab. 4 Simulation results of each scheme

Schemes	Type	Delay/s	Lane	Queue length/m
VBAL	LT cars	151. 30		
	LT buses	40. 80	LT	332. 9
	HT cars	133. 90	HT	470. 2
	HT buses	41. 89		
DLTL	LT cars	199. 58		
	LT buses	32. 80	LT	355. 8
	HT cars	172. 59	HT	467. 2
	HT buses	45. 21		
SLTL	LT cars	173. 19		
	LT buses	93. 39	LT	427. 9
	HT cars	132. 51	HT	433. 1
	HT buses	40. 19		

5 Conclusions

1) This paper presents a novel left-turning bus priority method called VBAL. Under this method, left-turning buses are provided with priorities by combining a variable lane and local pre-signal. Accordingly, the increase in through-vehicle delay can be minimized.

2) As an evaluation method, a cumulative curve was used to establish a delay calculation model. On this basis, the VBAL, DLTL, and SLTL schemes were compared through sensitivity analyses and case studies, and the results validated the feasibility of the VBAL scheme.

3) In the real world, variable areas are crowded with other vehicles, and a through vehicle getting stuck in a VBAL would occur. These problems need the implementation of electronic signs, movable guardrails, and other traffic facilities.

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基于动态车道的交叉口公交左转优先方法

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摘要：为减少左转公交延误，提高交叉口通行效率，提出了一种基于公交预信号的可变公交车道控制方法（VBAL）. 该方法将可变车道与公交优先预信号相结合，在不对其他车辆造成较大影响的基础上，实现了左转公交的优先通行. 给出了 VBAL 的渠化及控制方法，为验证该方法的有效性，将 VBAL 方案与单左转车道方案（SLTL）和双左转车道方案（DLTL）进行了比较. 在此基础上，利用累计曲线图示法建立了左转公交和直行车辆的延误变化计算模型. 通过灵敏度分析研究了车辆比例及绿信比对模型的影响. 结果表明，VBAL 方案能够在降低左转公交延误的同时，最大程度地减少直行车辆延误的增加. 利用 VISSIM 将该方案应用于实际路口，结果证实了 VBAL 方案的有效性和优越性.

关键词：交通工程；公交优先；动态车道；预信号；累积曲线

中图分类号：U491.3