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Research Article

Novel Design Method for Bus Approach Lanes with Bus Guidance and Priority Controls for Prioritizing Through and Left-Turn Buses

Shijie Shu, Jing Zhao, and Yin Han

Department of Traffic Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

Correspondence should be addressed to Jing Zhao; jing_zhao_traffic@163.com

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Transit priority is a useful way of improving transit operations in urban networks. However, the through and left-turn buses are rarely prioritized simultaneously at isolated intersections in the existing studies. This paper presents a variable bus approach lane design with a bus guidance and priority control model, which can reduce the delay of both the through and left-turn buses. The variable bus approach lanes can be dynamically used for the through and left-turn buses during the various periods of a signal cycle by the integrated design of geometric layouts and signal timing. A detailed bus guidance and priority control optimization model is formulated to guide the buses entering the appropriate bus approach lanes, and it provides optimal signal priorities for buses. The effectiveness of the proposed method is validated by a case study and numerical experiments. The results show that, on average, the total passenger delay can be reduced by 5% for every 30 veh/h and 40 veh/h increase in the volume of through buses and left-turn buses, respectively. Moreover, a comparison between the proposed method and the conventional transit priority method reveals that significant improvements can be made in reducing delays using the proposed method even at intersections with high degree of the saturation.

1. Introduction

With the increasing congestion on urban roads and the scarcity of the available land for road construction, more and more cities are seriously considering changing the mode of travel. Public transport is a cost-effective transit mode which is highly recommended by authorities and researchers [1–6]. Improving the service levels of public transits would encourage more citizens to choose public transport for their travels instead of private vehicles, which will alleviate traffic congestion. Use of bus lanes and provision of signal prioritization for buses are two common methods of improving public transit services.

Assigning bus lanes is a relatively economical and effective method, which has been examined in several studies [7]. Bus lanes can prevent private vehicles from interfering with buses and reducing the road space available to them. From the perspective of the geometric positions of bus lanes, exclusive bus lanes can be divided into four types: median, curbside, offset, and contraflow [8]. Among these, the median bus lane is least affected by private cars, for it can provide the highest quality bus services. If we consider the time-dependent function of bus lanes, they can be divided into two main types: dedicated and intermittent. The difference between these two is that, unlike the dedicated ones, bus lanes with intermittent priority are intermittently open to private vehicles when not used by a bus [9–15]. Therefore, when the bus frequency is not high, the intermittent bus lane does not significantly reduce street capacity.

In addition to assigning sections of the road to bus lanes, several unconventional intersection designs have also been proposed, which give preferential treatments to buses at intersections. The queue-jumper lane is a measure that designates a short stretch of a special lane to buses, such that they can bypass a traffic queue. This reduces the time spent in the queue [16–19]. The main design idea behind the queue-jumper lane is putting in place pre-signals before the main signal, such that private vehicles are controlled by the pre-signals. A bus advance area exists between the pre-signal and the main signal. In this way, buses can enter the bus advance area through the exclusive bus lane, which will reduce the time spent in the queue. Zhao and Zhou [20] presented a dynamic exclusive bus lane design in which the exclusive bus lane at the exit is dynamically used for left-turn buses and the opposing through buses. In this design, a pre-signal is set upstream of the intersection to control the left-turn buses entering the exclusive bus lane at the exit. Compared with the conventional bus lane design, over a 10% reduction of the total passenger delay time can be achieved under certain conditions. A novel method has been proposed [21] that provides priority to buses at signalized intersections using one approach lane, in which pre-signals are used to stop cars on the opposing travel lane. Buses can jump a portion of the cars using the opposing travel lane, which can reduce bus delays but has a negative impact on cars.

Besides assigning exclusive bus lanes, transit signal priority is another typical strategy used to reduce the transit delay at intersection. The existing transit signal priority strategies can be divided into three major types: passive priority strategies, active priority strategies, and real-time priority strategies [22]. The passive priority strategy does not require the detection of bus arrivals, and it has been proven to be effective when dwell times are predictable, and the bus frequencies are high [23]. However, passive priority strategies are not very adaptable when the vehicular flow is low. Correspondingly, active priority strategies, which need to detect the arrival of buses, can provide more effective priorities to buses. Active priority strategies include phase extension, phase advance, phase insertion, and phase rotation [24]. These strategies are more effective than passive priority strategies because they respond to traffic variations in real time. However, active priority strategies often have detrimental effects on the no-priority vehicles [25]. This shortcoming is the main limiting factor for its application. Real-time priority strategies have been developed that consider the total vehicular delay, or the total passenger delay at signal intersections. Real-time priority strategies optimize signal timings based on performance criteria, such as passenger delays, vehicular delays, and combinations of vehicular delays [26–31]. The integrated design of bus lanes and bus priority signal settings for isolated intersections have also been developed [21, 32], which can balance the performance of buses and cars and achieve higher intersection reserve capacity.

In recent years, with the advances in wireless communication technology, optimization methods have been proposed that operate in a connected vehicle environment. Hounsell and Shrestha [33] proposed a new bus priority strategy, which provides "differential" priority to buses, based on their own headway, and the headway of the following bus. Ma, Liu, and Han [34] assumed that the bus speed is available and can be adjusted in real time. A set of integrated operational rules, which integrate the operation of signal timings and bus speeds, have been developed to provide priority to buses at isolated intersections. Experimental analyses have shown that the proposed integrated operational rules perform better than the priority strategies, which do not adjust with the bus speed. He, Head, and Ding [35] presented a request-based, mixed-integer, linear program, which can coordinate multiple priority requests from pedestrians and different modes of transport. The simulation experiences show that all of the average passenger car delays, the average pedestrian delays, and the average passenger bus delays can be reduced. Hu, Park, and Lee [36] presented an optimization method for an intelligent transit signal priority logic that enables bus signal cooperation among consecutive signals. In this way, the bus delay saved at an upstream intersection will not be wasted at downstream intersections, which can efficiently reduce the bus delay. Wu, Ma, Long, and Wang [37] further presented a novel approach to minimize the weighted average vehicle delays of the intersection at isolated intersections under connected vehicle environment, in which the holding time at bus stops, signal timings, and bus speed are optimized simultaneously.

The transit signal priority strategies mentioned above have been proposed under the premise of using bus lanes. Although the existing design and control methods on the exclusive bus lanes can effectively improve the level of public transit service, there are two major shortcomings. One is that the bus-only approach lane can only be used for one bus movement, usually the through movement, while the left-turn buses have to mix with the mainstream left-turn vehicles. The other is that left-turn or through buses on the approach lanes at intersections can only pass through the intersection in one phase (left-turn or through phase) of a signal cycle.

In order to overcome the aforementioned problems, a novel bus approach lane design is proposed in this paper. These bus approach lanes are located on the left sides of exit and approach lanes. They can be dynamically used for the through and left-turn buses during various periods of a signal cycle [38, 39], which can ensure that both the left-turn and through buses can pass through the intersection by using the bus approach lanes during more than one signal phase. Therefore, the novel design is called variable bus approach lane (VBAL). To further improve the operational efficiency and stability, the corresponding bus guidance and priority controls are proposed, which are used to guide buses entering the appropriate bus approach lanes and going through intersections. An optimization problem of the multiple bus priority application was formulated as a mix-integer-non-linear-program (MINLP), which was solved by the enumeration method.

The rest of this study is organized as follows: In Section 2, the geometric design and phase plan of VBAL are presented. In Section 3, the operational optimization control model is presented. In Section 4, a case study is presented, whereby the variable bus approach lane design and priority control model are tested in an intersection in Shanghai, China. In Section 5, the sensitivity analysis of the proposed model is presented. The conclusions are outlined at the end of the paper.

2. Geometric Design and Phase Plan of VBAL

2.1. Geometric Design. The geometric design of the VBAL is depicted in Figure 1. Without loss of generality, the design is based on a four-leg intersection with median bus lanes. Two bus approach lanes (highlighted in yellow) and one exit lane

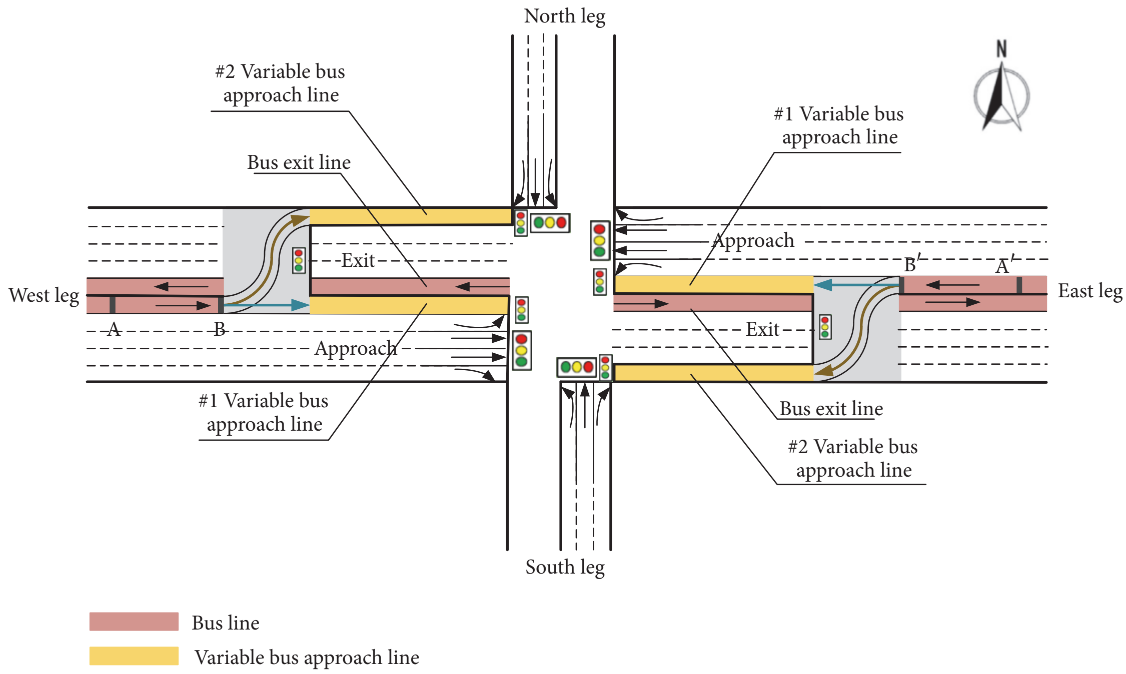


FIGURE 1: Geometric design of the variable bus approach lane.

(highlighted in red) are set on the west and east legs of the intersection. Compared with the conventional bus approach lane, the proposed VBALs have two characteristics: (i) the bus approach lanes are variable and can be used for through and left-turn buses during various periods of a signal cycle, and (ii) the Number 2 (#2) VBAL is located at the left side of the exit lanes. To ensure that buses enter the #2 VBAL safely and smoothly, a pre-signal is set upstream of the intersections. The pre-signal shows green for the opposing through traffic unless a bus is required to crossover to the #2 VBAL.

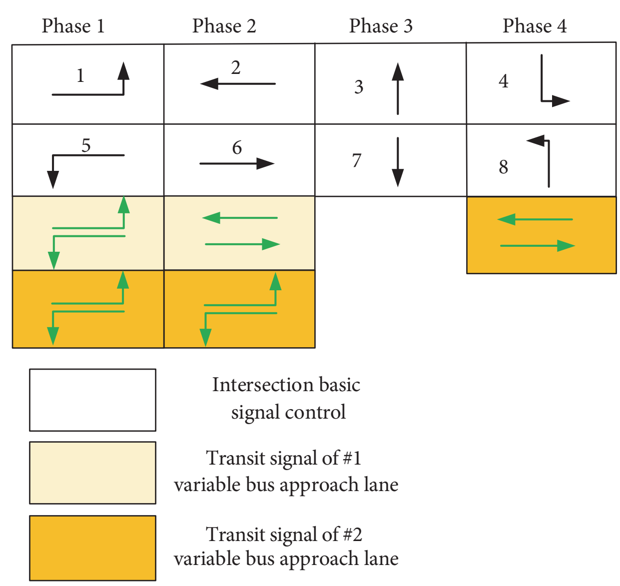


FIGURE 2: Phase plan of the intersection.

2.2. Phase Plan. The phase plan of the intersection is depicted in Figure 2. The conventional four-phase plan is used for the main intersection. The exclusive bus signals are set for the two variable bus approach lanes. In phase 1, left-turn buses on the #1 and #2 VBALs are allowed to pass through the intersection. In phase 2, the through buses on the #1 VBAL and left-turn buses on #2 VBAL are allowed to pass through the intersection. In phase 4, through buses on the #2 VBAL are allowed to pass through the intersection.

At the pre-signal, buses are guided to the specific VBAL. In phases 1 and 2, the through and left-turn buses enter VBALs Number 1 (#1) and #2, respectively. In phases 3 and 4, the through and left-turn buses enter the #2 and #1 VBALs, respectively. Detailed operational process of the proposed design is illustrated in Figure 3, in which the routes of the through and the left-turn buses are shown in blue and brown, respectively.

Moreover, to better visualize the proposed design, a video is provided. If you are located outside of mainland China, please visit https://youtu.be/jZcEIPViKfg. If you are located in mainland China, please visit http://v.youku.com/v_show/id_XNDA2Mzk4NTI0NA==.html?spm=a2hzp.8253869.0.0 (password: VBAL).

3. Optimization Control Model

Buses need to be controlled in order to ensure the efficient operation of the VBAL design. This includes two aspects of control: the VBAL selection guidance for buses and the transit signal control. For the bus guidance, although the function of the VBAL changes in one cycle, the function is fixed in a phase

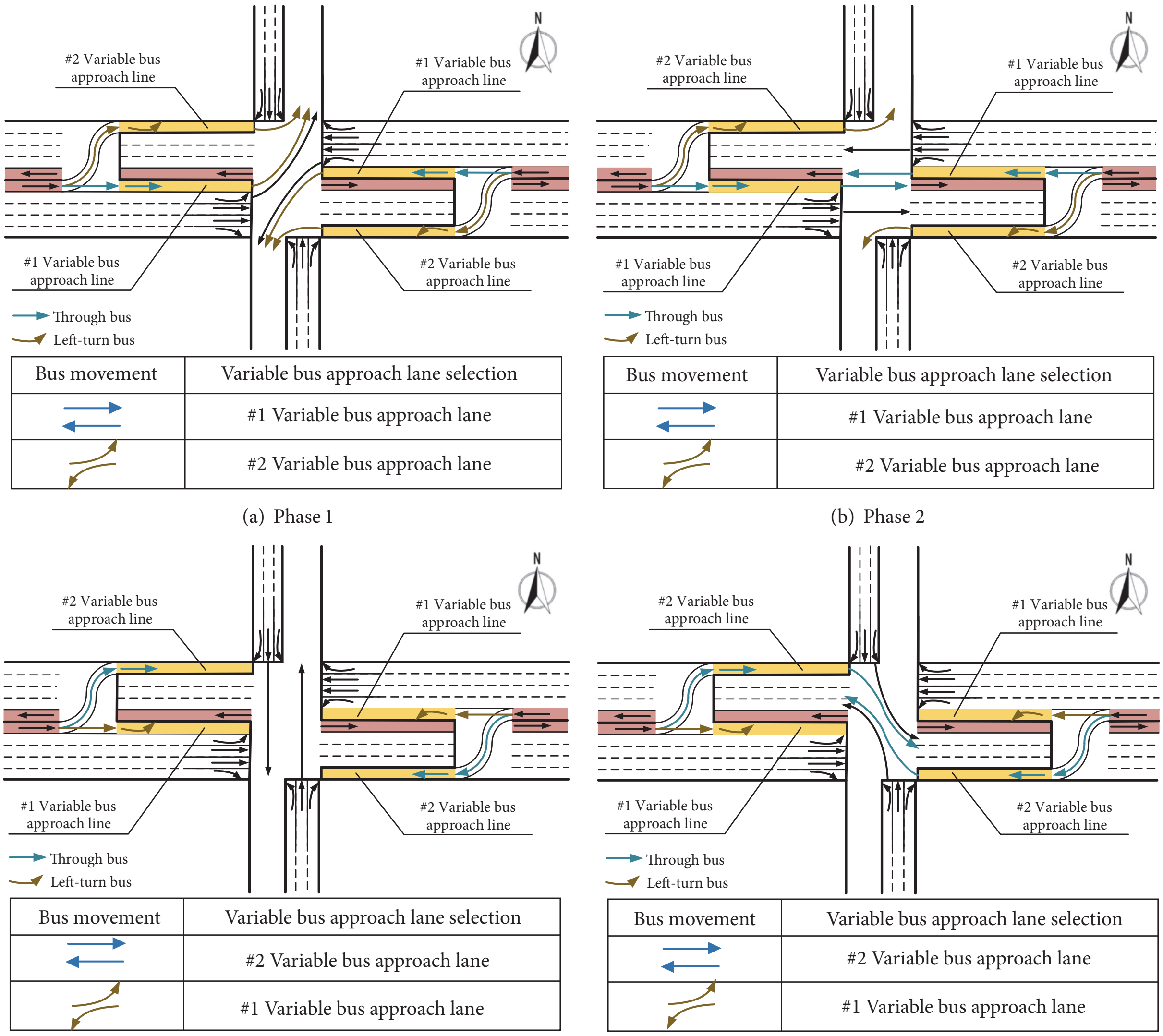


Figure 3: Operational process.

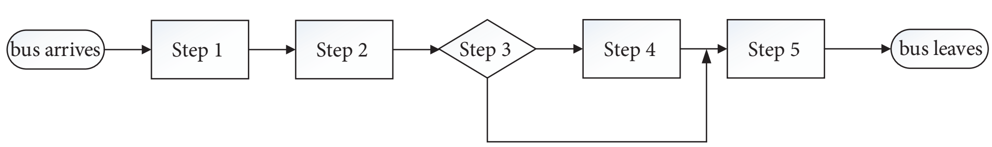


Figure 4: The operational optimization control model of VBAL.

of a cycle, and the arrival of the buses is random. Therefore, it is necessary to guide the bus to the appropriate VBAL. For the transit signal control, the bus signal priority will be considered to improve the overall efficiency of the intersection on the basis of ensuring that buses are not stranded. As depicted in Figure 4, the operational optimization control model of VBAL can be divided into five steps.

To facilitate the model presentation, notations used hereafter are summarized in Table 1. The notations used in the model are divided into three categories: input parameters, intermediate variables, and decision variables.

3.1. Step 1. In this step, the state of the bus is detected. When there is a bus passing through the detection point A (as shown

Table 1: Notation of key model parameters and variables.

Symbol	Definition
Input parameters	
M	Set of bus movements
$d \in M$	Index of bus movements, $d = 1$ for westbound left-turn, $d = 2$ for westbound through, $d = 3$ for eastbound left-turn, $d = 4$ for eastbound through
N	Set of private vehicle movements
$j \in N$	Index of private vehicle movements, $j = 1$ for movement 1, $j = 2$ for movement 2, . . ., $j = 8$ for movement 8, see Figure 10(b)
q_j	Arrival rate for vehicular movement j (veh/s)
s_j	Saturation flow for movement j (veh/s)
C	Cycle length (s)
g_j	Length of green time for movement j (s)
P_a	Average passenger occupancy of private vehicles (per/veh)
P_b	Passenger occupancy of buses (per/veh)
d_v	Space headway for queuing vehicles (m)
$L_{max,j}$	Queue length limitation for movement j (m)
g_p^{min}	Minimum green time for pedestrian crossing the street (s)
v	The speed of bus (m/s)
L	The distance from detection point to intersection stop line (m)
t_0	The relative time in the signal cycle when the bus arrives at the detection point A (s)
$g_{e1}, g_{e2}, g_{e3}, g_{e4}$	The relative time in the signal cycle when phase 1, phase 2, phase 3, phase 4 end (s)
Intermediate variables	
S	Set of vehicular operating phases
$k \in S$	Index of vehicular operating phases at the main intersection, $k = 1$ for phase 1, $k = 2$ for phase 2,..., $k = 4$ for phase 4, see Figure 3
p	Set of bus signal priority categories
$r \in p$	Index of bus signal priority categories, $r = 0$ for no bus signal priority, $r = 1$ for early green, $r = 2$ for green extension
$\Delta t_{d,r,j}^k$	Length of bus priority time (s)
$l_{max,j}^r$	Largest queue length of movement j under the priority categories r (m)
$h_{A,j}^r, h_{B,j}^r, h_{C,j}^r, h_{D,j}^r, h_{E,j}^r, h_{F,j}^r$	Cumulative number of vehicles of movement j at points A, B, C, D, E and F under the priority categories r
$t_{1,j}^r, t_{2,j}^r, t_{3,j}^r$	Time of queue dissipation of movement j under the priority categories r (s)
$S_{1,j}^r, S_{2,j}^r$	Increased delay of movement j under the priority categories r (s)
t	The length of time required for a bus from the detection point to the stop line (s)
t_c	Relative time in the signal cycle when the bus arrives at the intersection (s)
Decision variables	
ΔD_a	Passenger delay increment of private vehicles at the intersection (s)
ΔD_b	Passenger delay increment of buses at the intersection (s)

in Figure 1), the speed and the movement of the bus are detected.

3.2. Step 2. In this step, the estimated arrival time and the signal phase that bus will meet when it arrives at the main intersection can be obtained.

The time that the bus arrives at the intersection can be estimated by (1). Through the speed of bus and the distance from detection point to intersection stop line, the arrival time can be estimated. Then, based on the estimated arrival time and the signal timing of the main intersection, the signal phase that bus will meet when it arrives at the main intersection can be estimated by (3). In (2), t_0 is the relative

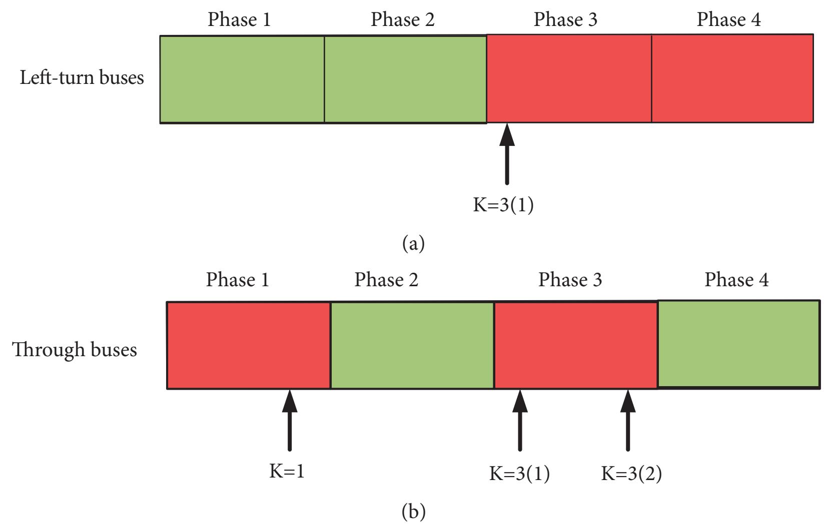


Figure 5: Phases of application priority.

time in the signal cycle when the bus arrives at the detection point A. t_c is the relative time in the signal cycle when the bus arrives at the intersection. In (3), k = 3(1) and k = 3(2) represent the first half and second half of phase 3, respectively.

$$t = \frac{L}{v} \tag{1}$$

$$t_c = \operatorname{mod}\left(\frac{t + t_0}{C}\right) \tag{2}$$

$$k = \begin{cases} 1 & (0 \le t_c < g_{e1}) \\ 2 & (g_{e1} \le t_c < g_{e2}) \\ 3\,(1) & (g_{e2} \le t_c < g_{e2} + 0.5 * g_3) \\ 3\,(2) & (g_{e2} + 0.5 * g_3 \le t_c < g_{e3}) \\ 4 & (g_{e3} \le t_c < g_{e4}) \end{cases} \tag{3}$$

3.3. Step 3. In this step, according to the bus movement and the signal phase that bus will meet when it arrives at the main intersection, the type of priority can be obtained.

Only two types of signal priority strategies are considered in this research, green extension and early green. As depicted in Figure 5, the left-turn buses will apply for the green extension in phase 3(1). For the through buses, it will apply for the green extension in phase 3(1) and apply for the early green in phase 1 and phase3(2).

As depicted in Figure 6, the left-turn bus which will meet phase 1 when it arrives at the intersection will not apply for priority. The left-turn bus which will meet phase 3(1) when it arrives at the intersection will apply for green extension. Depending on whether signal priority is required, all left-turn and through buses can be divided into two types: (i) The buses which do not need priority go to step 5, and (ii) the buses which need priority go to step 4.

3.4. Step 4. In this step, the bus signal priority application will be brought into the optimization model and then judge whether the signal priority application is passed or not.

The optimization model is used to solve the multiple bus priority application. In one signal cycle, there may be multiple bus priority requests. In this step, it follows the principle that the green extension application will be processed first, and the early green application will be processed when there is no green extension application. It means that the optimization model only processes one type of signal priority strategies at a time. When there are multiple bus priority applications of the same type (for example, green extension), they are brought into the optimization model. The optimization model will select the priority application which minimizes the total passenger delay of the intersection.

3.4.1. Objective Function. The proposed model aims to minimize the total passenger delay increment at the main intersection. The total passenger delay increment is defined as the delay in instances when the bus priority strategy is adopted at intersections, minus the delay in instances when no bus priority is allocated at intersections. Therefore, the value of the total passenger delay increment should be negative when the transit signal priority strategy is adopted. The total passenger delay increment was used as an indicator and comprised two parts: (1) the passenger delay increment of private vehicles at the intersection and (2) the passenger delay increment of buses at the intersection.

$$\min \Delta D_a + \Delta D_b \tag{4}$$

3.4.2. Constraints

(1) The Calculation of the Delay. Only two kinds of priority strategies (green extension, early green) are used in the

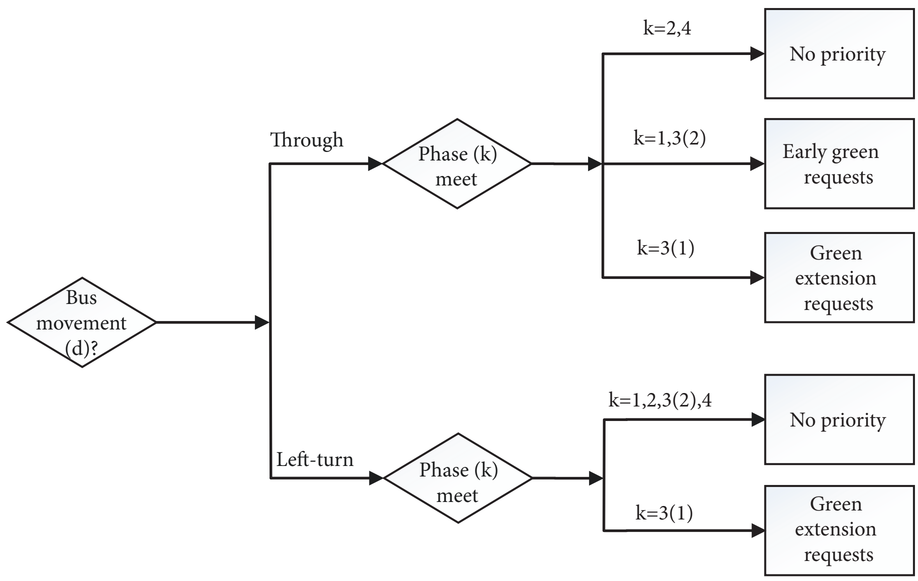


Figure 6: Types of bus application priority.

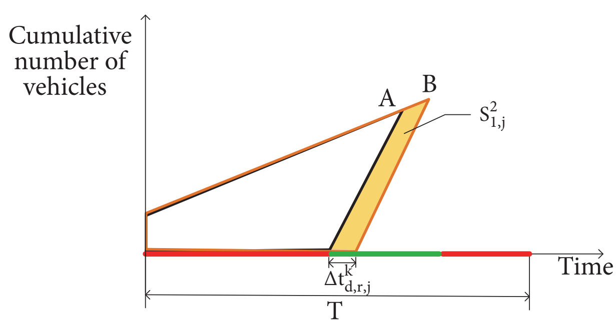


Figure 7: Calculation of vehicular delay under the green extension.

optimization model. The calculations of these two priority strategies are as follows.

As displayed in Figure 7, the area of the yellow part, $S^2_{1,j}$, is the delay increment caused by the extension of the green light. The passenger delay increment of private vehicles on movement j can be calculated by

$$\Delta D_a = P_a \bullet S^2_{1,j} \tag{5}$$

The $S^2_{1,j}$, variables in (5) can be calculated using (6). The intermediate variables, $h^2_{A,j}$, and $h^2_{B,j}$, are the cumulative numbers of vehicles on movement j at points A and B, which can be calculated by (7) and (8), respectively.

$$S^2_{1,j} = \frac{1}{2}\left(C - g_j + \Delta t^k_{d,r,j}\right) h^2_{B,j} - \frac{1}{2}\left(C - g_j\right) h^2_{A,j} \tag{6}$$

$$h^2_{A,j} = \frac{s_j q_j \left(C - g_j\right)}{s_j - q_j} \tag{7}$$

$$h^2_{B,j} = \frac{s_j q_j \left(C - g_j + \Delta t^k_{d,r,j}\right)}{s_j - q_j} \tag{8}$$

As illustrated in Figure 8, the areas of the yellow part, $S^1_{1,j}$ and $S^1_{2,j}$, are the delay increments caused by the advance of the green light. The passenger delay increment of private vehicles on the movement j can be calculated by

$$\Delta D_a = P_a \bullet \left(-S^1_{1,j} + S^1_{2,j}\right) \tag{9}$$

The variables $S^1_{1,j}$ and $S^1_{2,j}$ in (9) can be calculated using (10) and (11), respectively. The intermediate variables $h^1_{A,j}$, $h^1_{B,j}$, $h^1_{C,j}$, $h^1_{D,j}$, $h^1_{E,j}$, and $h^1_{F,j}$ are the cumulative numbers of vehicles for movement j at points A–F, which can be calculated by (12)-(16), respectively. The intermediate variables $t^1_{1,j}$, $t^1_{2,j}$, $t^1_{3,j}$, and $t^1_{4,j}$ are the queue dissipation times for movement j, which can be calculated by (17)-(20), respectively.

$$S^1_{1,j} = \frac{1}{2}\left(h^1_{A,j} - h^1_{C,j}\right)\left(t^1_{2,j} - t^1_{1,j}\right) \tag{10}$$

$$\begin{aligned} S^1_{2,j} = {} & \frac{1}{2}\left(C - g_j + t^1_{4,j}\right)\left(h^1_{D,j} + h^1_{F,j}\right) \\ & - \frac{1}{2}\left(C - g_j\right) h^1_{E,j} - \frac{1}{2} t^1_{4,j} h^1_{F,j} \end{aligned} \tag{11}$$

$$h^1_{A,j} = \left(C - \Delta t^k_{d,r,j}\right) q_j \tag{12}$$

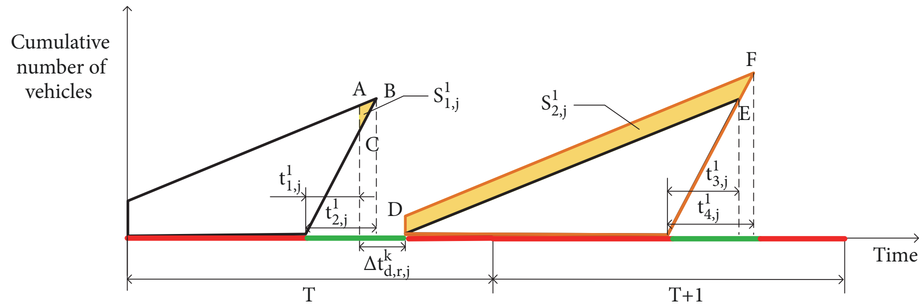


Figure 8: Calculation of vehicular delay under the early green.

$$h^1_{C,j} = \left(g_j - \Delta t^k_{d,r,j}\right) s_j \quad (13)$$

$$h^1_{D,j} = h^1_{A,j} - h^1_{C,j} + q_j \Delta t^k_{d,r,j} \quad (14)$$

$$h^1_{F,j} = t^1_{4,j} s_j \quad (15)$$

$$h^1_{E,j} = t^1_{3,j} s_j \quad (16)$$

$$t^1_{1,j} = g_j - \Delta t^k_{d,r,j} \quad (17)$$

$$t^1_{2,j} = \frac{q_j \left(C - g_j\right)}{s_j - q_j} \quad (18)$$

$$t^1_{3,j} = t^1_{2,j} = \frac{q_j \left(C - g_j\right)}{s_j - q_j} \quad (19)$$

$$t^1_{4,j} = \frac{q_j \left(C - g_j\right) + h^1_{D,j}}{s_j - q_j} \quad (20)$$

The passenger delay decrement of buses on the movement j can be calculated by

$$\Delta D_b = P_b \bullet \left(C - g_j - \Delta t^k_{d,r,j}\right) \quad (21)$$

(2) The Length of Bus Priority Time Constraints. The adoption of bus signal priority (including early green and green extension) leads to longer queue lengths for the adjacent flows. Multiple cycles are required for the long queue lengths to be restored to zero, which results in large delay increments. In order to avoid increasing the intersection delay too much, the lengths of early green and green extension need to be constrained by (22) and (23), respectively.

As shown in (12), after adopting the early green, the queue length of movement j can be restored to zero before the end of the green light period, which can serve j in the second cycle. Similarly, after adopting the green extension, the queue length of movement j can be restored to zero before the end of the green light period, which can serve j in the first cycle, as shown in (23).

$$\Delta t^k_{d,r,j} \le 2 \frac{s_j g_j - q_j C}{s_j} \qquad \forall j \in N,\ k \in S,\ r \in \{1\},\ d \in M \quad (22)$$

$$\Delta t^k_{d,r,j} \le \frac{s_j g_j - q_j C}{s_j} \qquad \forall j \in N,\ k \in S,\ r \in \{2\},\ d \in M \quad (23)$$

(3) Queue Length Constraints. In order to avoid vehicle queue spillovers, the queue length of any particular movement cannot be greater than the maximum queue length limit, $L_{max,j}$, as shown in

$$l^r_{max,j} \le L_{max,j}, \quad \forall j \in N,\ r \in \{1,2\} \quad (24)$$

(4) The Minimum Green Time Constraints. The minimum green time period should be larger than or equal to the minimum green light period needed for pedestrians to cross the street, as shown in

$$g_j - \Delta t^k_{d,r,j} \ge g^{min}_p \qquad \forall j \in N,\ k \in S,\ r \in \{1,2\},\ d \in M \quad (25)$$

(5) The Phase Plan Constraints. The green time under the phase plan should meet constraint (26) due to the setting of the barriers displayed in Figure 2.

$$g_{j-1} + g_j + \Delta t^k_{d,r,j} = g_{j+3} + g_{j+4} + \Delta t^k_{d,r,j+4} \qquad \forall j \in \{2,4\},\ k \in \{4\},\ r \in \{2\},\ d \in M \quad (26)$$

In order not to affect the normal operation of vehicles in the adjacent cycles, the intersection will not adopt bus priority in phases 1 and 4.

$$\Delta t^k_{d,r,j} = 0 \qquad \forall j \in \{1,5,4,8\},\ k \in \{1,4\},\ r \in \{1,2\},\ d \in M \quad (27)$$

Table 2: Guidance for the buses of lane selection.

Movement	Signal phase	No priority	Priority application passed	Priority application rejected
Left-turn	1	#2	-	-
	2	#2	-	-
	3(1)	-	#2	#1
	3(2)	#1	-	-
	4	#1	-	-
Through	1	-	#1	#1
	2	#1	-	-
	3(1)	-	#1	#2
	3(2)	-	#2	#2
	4	#2	-	-

Table 3: Traffic parameters of the tested intersection.

Leg	Movements	Bus lines	Private vehicle volume (veh/h)	Bus volume (veh/h)
East	Left-turn	Line 748,91,196	136	20
	Through	Line 71,776,865, SQ	770	30
	Right-turn	Line MH18, HQ1	300	9
West	Left-turn	N/A	104	0
	Through	Line 71,776,865, SQ	898	28
	Right-turn	Line MH33	240	6
North	Left-turn	Line MH18, 173	380	6
	Through	Line HQ4, 189	624	18
	Right-turn	Line HQY	77	4
South	Left-turn	Line MH33	190	6
	Through	Line HQ4, 189	504	18
	Right-turn	Line 91, 748, 196	128	12

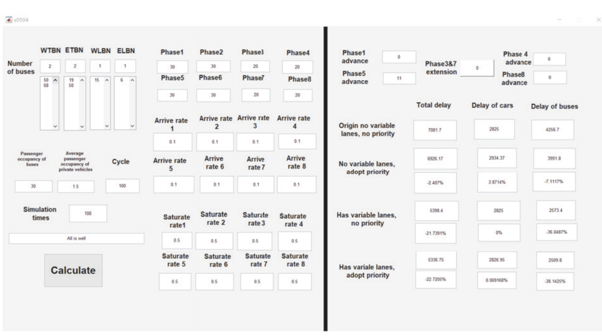


Figure 9: Program running interface.

3.4.3. Solution. The variable bus approach lane selection model (including the optimization model) was coded in MATLAB and tested on an Intel i5, 2.5 GHz processor and 20.0 GB RAM, running under Windows. The program's running interface is presented in Figure 9.

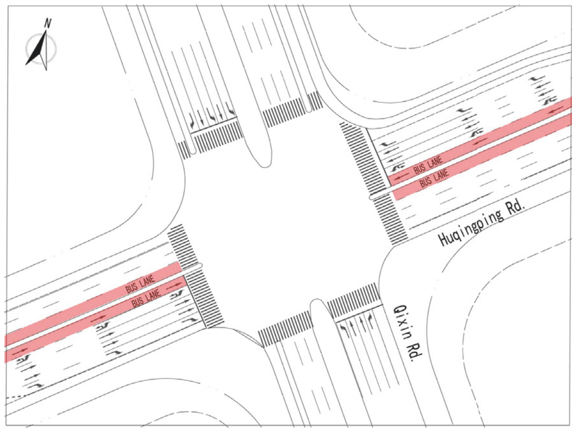
3.5. Step 5. In this step, the buses will be guided to the appropriate VBALs, and the signal timing of intersection will be adjusted according to priority applications.

As depicted in Table 2, the buses will be guided to the appropriate VBALs. The value of min $\Delta D_a + \Delta D_b$ is calculated in the previous step. If min $\Delta D_a + \Delta D_b \leq 0$, it means that the bus signal priority will not increase the total passenger delay increment at the main intersection, so the bus signal priority will be passed. Otherwise, the bus signal priority will be rejected. If the bus signal priority is passed, signal timing of intersection will be adjusted according to priority applications.

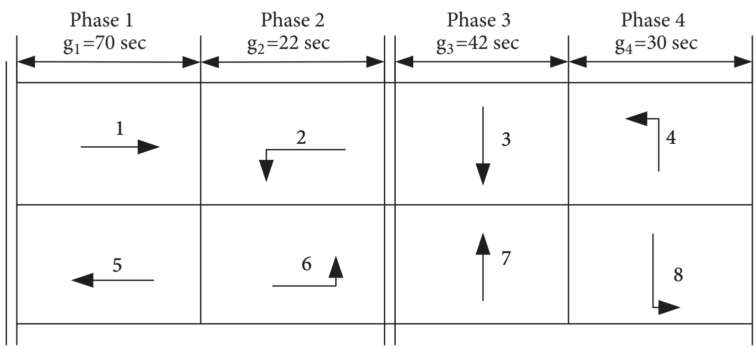
4. Case Study

The effectiveness of the VBAL design and the bus guidance and priority control model was evaluated by a real-world intersection, namely, the intersection of the Qixin and Huqingping roads located in Shanghai, China. The layout of the intersection is presented in Figure 10(a). The exclusive center bus lane is located on Huqingping road. Traffic volumes during the peak hours (8 to 9 a.m.) were obtained based on a field survey, as shown in Table 3. The saturation rate of each lane was 1800 veh/h, and the average passenger occupancies of private vehicles and buses were set to 1.5 per/veh and 30 per/veh, respectively.

The intersection was operated on a fixed four-phase cycle with a cycle length of 180 s, as presented in Figure 10(b). The proposed VBAL method was applied to the intersection, and the optimized geometric design and the signal timings are shown in Figure 11.



(a) Original layout



(b) Original signal timing

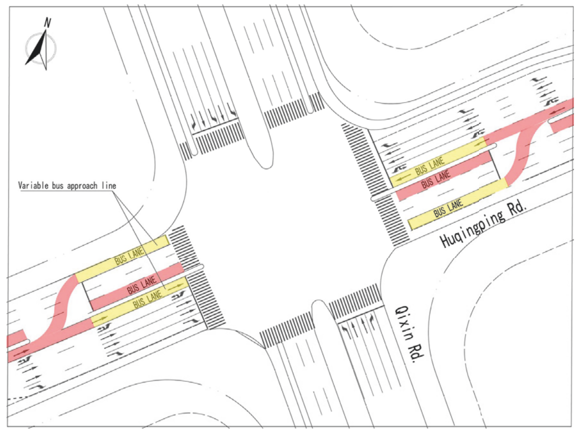
FIGURE 10: Original layout and signal timings of the tested intersection.

TABLE 4: Comparisons of three models about delay variation.

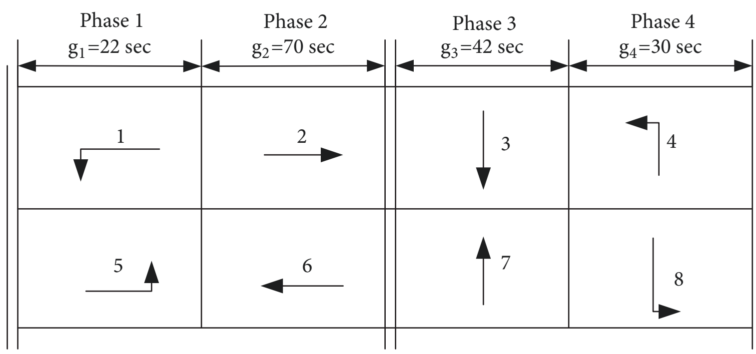
Schemes	Index	Average passenger delay for all vehicles (s)	Average private vehicle passenger delay (s)	Average bus passenger delay (s)
Original	Mean	48.1	48.0	48.2
Scheme 1	Mean	44.7	48.7	38.7
	variation	-7.1%	1.5%	-19.7%
Scheme 2	Mean	39.3	48.4	25.9
	variation	-18.3%	0.8%	-46.2%
Scheme 3	Mean	36.0	49.5	16.2
	variation	-25.2%	3.1%	-66.4%

The microscopic simulation package VISSIM 5.40 was used and calibrated as the unbiased evaluator to evaluate the performance of the proposed model (Scheme 3) and to compare it with the other three designs: Scheme 2, Scheme 1, and the original scheme. In Scheme 3, VBALs are located at the intersection, and the bus signal priority is also adopted. In Scheme 2, VBALs are also located at the intersection with the difference that bus signal priority is not adopted. In Scheme 1, there are no VBALs at the intersection, but the bus signal priority is adopted. The original scheme is the method which does not have VBALs at the intersection and does not adopt bus signal priority.

Using the average passenger delay as the indicator, the comparison results are shown in Table 4. Schemes 2 and 3 reduced the average vehicular passenger delays by 18.3% and 25.2%, respectively. By contrast, Scheme 1 only yielded a 7.1% reduction in the average vehicular passenger delay. Using the average bus passenger delay as the indicator, the percentage of the average bus passenger delay decrement for Schemes 2 and 3 was -46.2% and -66.4%, respectively, which is much



(a) Optimized layout



(b) Optimized signal timing

FIGURE 11: Optimized layout and signal timing of the tested intersection.

larger than the -19.7% for Scheme 1. From the perspective of the average private vehicle passenger delay, the percentages of the average private vehicle passenger delay increments caused by the three schemes were not very different and were all less than 5%.

5. Sensitivity Analysis

A sensitivity analysis was conducted in order to analyze the impacts of the arrival rate of buses and the intersection saturation on the efficiency of the proposed method. Therefore, the proper application domains of each of the optimization schemes can be identified. In this section, the geometry of the intersection is described in Figure 11(a). The arrival rate of private vehicles for each movement is set to 360 veh/h, the saturation rate of each movement is set to 1800 veh/h, and the average passenger occupancy of private vehicles and buses is set to 1.5 per/veh and 30 per/veh, respectively. The cycle length is set to 100 s, the four-phase plan is described in Figure 11(b), and the duration of each phase is set to 25 s. In addition, in Figures 13 and 14(a), the arrival rates of private vehicles for each movement are from 284 to 425 veh/h depending on the saturation. In Figure 14(a) , the arrival rate of buses (including left-turn and through) is set to 80 veh/h. In this section, the schemes are as described in Section 4.

Figure 12 shows the impacts of the bus arrival rates (including left-turn and through movements) on the proposed method's (Scheme 3) performance. It can be observed that the percentage of reduction of the total passenger delay increases with the increase in the number of left-turn and through buses. On average, for every 30 veh/h increase in the arrival rate of through buses, the total passenger delay is reduced by 5%. Similarly, for every 40 veh/h increase in the arrival rate of left-turn buses, the total passenger delay is reduced by 5%. The reason for the decrease in the total passenger delay time with the increase in the bus arrival rate is as follows: as the bus arrival rate increases, the proportion of bus passengers among all passengers also increases, which results in a reduction in the total passenger delay at the intersection.

Figure 13 presents the impacts of the bus arrival rate and the degree of saturation on the performance of the proposed model. Overall, the percentage of reduction of the total passenger delay increases with the increase in the number of left-turn and through buses and decreases with the increase in the degree of saturation. On average, for every 0.1 increase in the degree of saturation, the percentage of reduction of the total passenger delay is reduced by 3.94%. Moreover, to gain a certain percentage of reduction of the total passenger delay, the required number of bus arrival rate increases rapidly with the increase of the degree of saturation. For example,

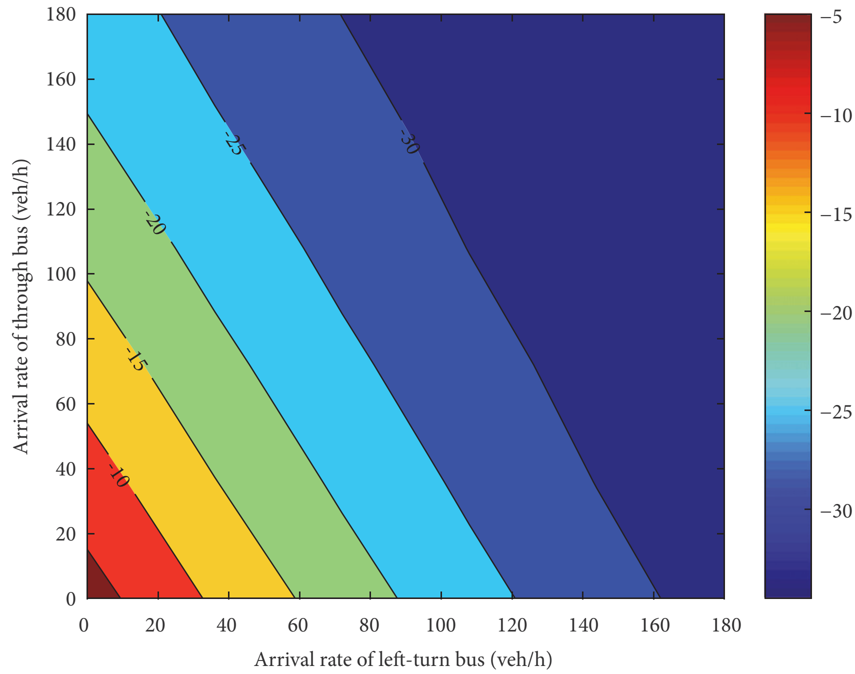


Figure 12: Impact of bus arrival rate. Note: the colors illustrate the percentages of reduction of the total delay, which is defined as the ratio of the delay in Scheme 3 to the delay in the original scheme.

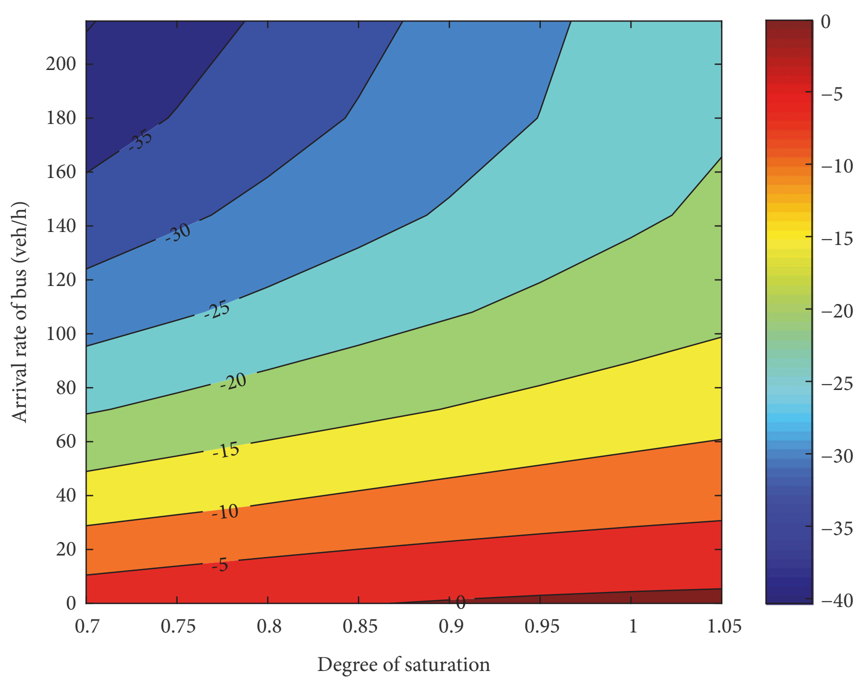
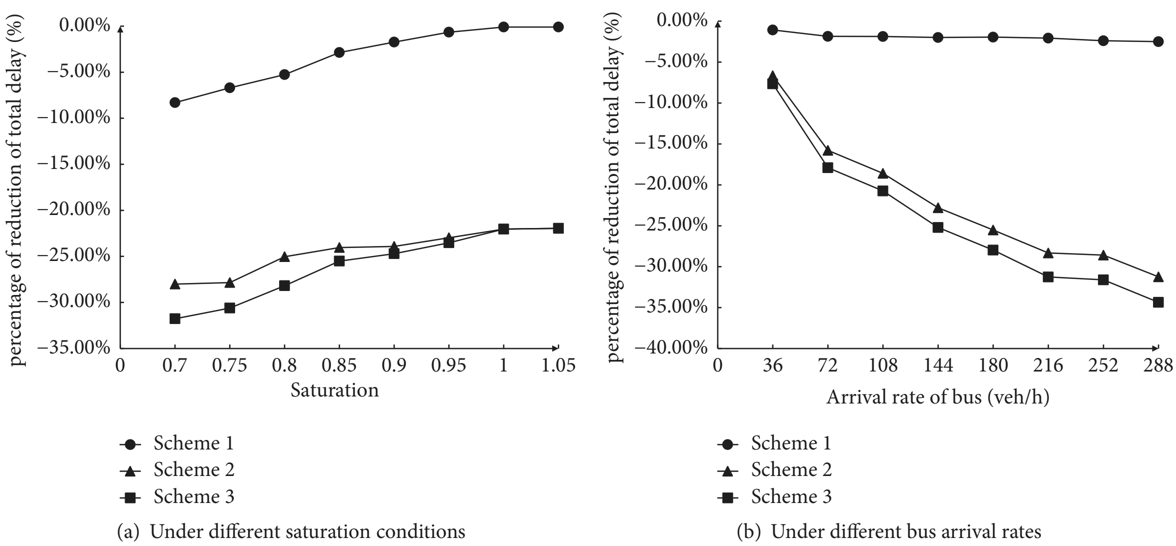


Figure 13: Impact of bus arrival rate and degree of saturation. Note: the colors illustrate the percentages of reduction of the total delay, which is defined as the ratio of the delay in Scheme 3 to the delay in the original scheme.

if the percentage of reduction of the total passenger delay is 25%, the increased number of required bus arrival rate is 22 veh/h, 34 veh/h, and 106 veh/h when the degree of saturation changes from 0.7 to 1.0 by using 0.1 as the interval, respectively.

Figure 14 presents a comparison of the three schemes. As Figure 14(a) shows, there is a significant difference in the delay reductions under different schemes when saturation is less than 0.8. All three schemes are effective, but Schemes 3 and 1 are the most and least effective methods, respectively.



(a) Under different saturation conditions

(b) Under different bus arrival rates

Figure 14: Comparison of the proposed model to the conventional model.

Bus arrival rate (veh/h) \ Degree of saturation	0.7	0.75	0.8	0.85	0.9	0.95	1	1.05
216	-40.45%	-35.36%	-35.45%	-30.85%	-29.80%	-28.05%	-25.02%	-24.60%
180	-36.10%	-32.86%	-32.40%	-28.13%	-25.28%	-23.95%	-22.26%	-21.92%
144	-34.18%	-32.08%	-30.57%	-26.72%	-25.88%	-22.06%	-19.89%	-19.36%
108	-26.40%	-25.77%	-23.00%	-21.33%	-18.60%	-17.49%	-16.11%	-15.03%
72	-23.01%	-21.45%	-19.12%	-17.10%	-16.16%	-14.01%	-12.41%	-11.66%
36	-12.35%	-10.56%	-9.53%	-8.64%	-8.17%	-6.30%	-6.00%	-5.88%
0	0	0	0	0	0	0	0	0

Figure 15: Table with recommended scope of use of Scheme 3. Note: the percentage of reduction of total delay is defined as the ratio of the delay in Scheme 3 to the delay in the original scheme.

The percentage of reduction in the delay decreases when there is an increase in the intersection saturation. When the saturation is between 0.8 and 0.95, the gap between Schemes 2 and 3 becomes smaller, and Scheme 1 has almost no effect. When the saturation is greater than 0.95, Scheme 1 has no effect, while Schemes 2 and 3 are clearly effective (more than 16%), and the difference in their effectiveness is very small. It can be seen that as the saturation increases, the effect of bus signal priority worsens. When the saturation is greater than 0.95, the bus signal priority has little effect and the geometric design of VBAL plays a major role. Therefore, Scheme 2 can be adopted when the saturation of the intersection is very high, because its effectiveness is not very different from that of Scheme 3. As Figure 14(b) shows, as the bus arrival rate increases, Schemes 2 and 3 gain more advantages over Scheme 1, especially when the bus arrival rate is over 72 veh/h.

Figure 15 presents the recommended scope of use for Scheme 3, which can provide suggestions for practical applications. Figure 15 contains three parts: the green part shows suitability of application for Scheme 3, the red part shows unsuitability of application for Scheme 3, and the yellow part indicates that the percentage of reduction of the total delay is between 10% and 20%. In the yellow part, the effect of Scheme 3 is minor. As shown in Figure 15, when the bus arrival rate is over 108 veh/h, over a 15% reduction in the total passenger delay can be obtained.

6. Conclusions

A novel bus approach lane design with a bus guidance and priority control model, in which variable bus approach lanes can be dynamically used for through and left-turn buses, is presented in this paper. A detailed bus guidance and priority control optimization model was developed to guide buses entering the appropriate bus approach lanes and to provide optimal signal priority for buses. A case study and numerical experiments were conducted to evaluate the effectiveness of the proposed method and to compare it with conventional methods. The following conclusions can be drawn from the results:

(1) The proposed model can reduce the delay of both through and left-turn buses while maintaining the operational performance for private vehicles by the design of variable bus approach lanes and guidance for buses. The VBALs can be dynamically used for the through and left-turn buses during the various periods of a signal cycle. In this way, both sets of buses can pass through intersections by using the VBALs during more than one signal phase.

(2) Overall, the percentage of reduction of the total passenger delay increases with the increase in the number of left-turn and through buses and decreases with the increase in the degree of saturation of the intersection. On average, the total passenger delay can be reduced by 5% for every 30 veh/h and 40 veh/h increase in the volume of through buses and left-turn buses, respectively. When the bus arrival rate is over 108 veh/h, the proposed method is very effective and can yield over a 15% reduction in the total passenger delay. However, for every 0.1 increase in the degree of saturation, the percentage of reduction of the total passenger delay is reduced by 3.94%.

(3) Compared with the conventional transit priority strategies, the new design is shown to be effective in reducing passenger delay under high traffic demand levels. When degree of saturation is greater than 0.95, the conventional method has almost no effect, while the proposed method is clearly effective (about 16%). Moreover, under the condition that the degree of saturation is high, the geometric design of VBALs plays a major role, while the bus signal priority has little effect.

It is necessary to be able to guide buses when running the proposed method. Therefore, bus drivers need to be educated and trained before the proposed method can be implemented. This method is deemed feasible because bus drivers are skilled drivers and bus lines are fixed. In the future, the authors also plan to analyze the impact of drivers' mistakes and to propose the corresponding countermeasures. Moreover, with the development of intelligent vehicle infrastructures, cooperative technology, and driverless technology, the proposed method will be more readily applicable.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors confirm that the mentioned received funding in the Acknowledgments section did not lead to any conflicts of interest regarding the publication of this manuscript.

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