Research Article

Capability of Intermittent Bus Lane Utilization for Regular Vehicles

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Received 18 February 2022; Revised 10 May 2022; Accepted 13 May 2022; Published 25 May 2022

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Intermittent bus lanes (IBLs) can improve road capacity by allowing other regular vehicles to drive in the idle space of a dedicated bus lane. However, excessive vehicles in the IBL will cause additional bus delays. To avoid such problems, this study proposes a method to determine the capability of IBL permitted for regular vehicles first, and then use it as the total amount restriction of lane-borrowing vehicles to implement a bus lane control strategy that will improve road capacity and avoid additional bus delays. A model for calculating the capability of IBL is also provided. Vehicles between two buses are designated as potentially lane-borrowing vehicles that could follow the buses to leave the road section. The evolution process of these vehicles in the unit is analyzed using kinematic wave theory to obtain the formed traffic queue length. Using the rear bus trajectory to set the length limit on the traffic queue, the estimated total amount of lane-borrowing vehicles is corrected to establish the final capability of the IBL.

The applicability of the method was evaluated from three perspectives: bus departure interval, road traffic saturation, and near-side bus stop. The simulation results showed that the proposed method can guarantee no additional bus delay compared to the situation of a dedicated bus lane. It can also improve road capacity more than traditional IBL under any degree of saturation and bus departure interval. Compared with traditional IBL, the average travel time of regular vehicles is shorter, except when the degree of saturation is high and the bus departure interval is large.

1. Introduction

A dedicated bus lane (DBL) [1] ensures stable operation of public transport. However, in practice, due to limited urban road resources, permanently setting the DBL can reduce the traffic capacity of regular lanes. When regular vehicles are congested, yet the bus service frequency is low and bus lanes cannot be fully utilized, the DBL is seen to be an aggravating waste of road resources. To address this issue, Viegas and Lue [2, 3] proposed the intermittent bus lane (IBL) method and provided a real-world demonstration in Lisbon as a prototype [4]. When the bus reaches upstream of the road section that is being allowed for dual use by buses and regular vehicles, one lane of the road section becomes dedicated to the bus. When a bus leaves the road section, regular vehicles are permitted to borrow bus lanes to drive, which improves the traffic capacity of the bus lane. Since then, many studies have been conducted to improve the IBL method. The goal is to reduce the additional bus delay caused by lane-borrowing vehicles (referred to as additional bus delays) and simultaneously increase the total amount of lane-borrowing vehicles.

Some IBL methods require vehicles to meet certain control rules before entering the bus lane to ensure the number of lane-borrowing vehicles does not hinder the rear bus. For example, the control rule of IBL [2] is to demarcate a distance in front of the rear bus in the bus lane that regular vehicles cannot enter; all lane-borrowing vehicles maintain a buffer space with the rear bus when entering the bus lane, thereby reducing the obstruction to the rear bus. The bus lane with time-division multiplexing (BLTDM) method proposed by Dong and Zhao [5, 6] stipulates that regular vehicles whose travel time on the road section does not exceed the travel time of the bus are permitted to enter the bus lane. They believe that these vehicles can reach the end of the road before the rear bus and will not cause additional bus
delays. This was determined when the bus reached a certain point upstream of the section, the location of which is related to the travel time of lane-borrowing vehicles and the rear bus on the road section. However, this rule ignores the fact that driving lane-borrowing vehicles is a dynamic evolution process, and it cannot be guaranteed that a judgment at a certain moment during the entire drive of such vehicles will not hinder the rear bus.

To reduce additional bus delays, some methods reduce the queuing time of buses through intersection control measures for public transport. However, such approaches, including transit signal priority (TSP) [7–10] and road-space priority (RSP) [11–13], are not effective for saturated traffic conditions. Other methods attempt to force excessive regular vehicles in a certain range in front of the rear bus (the clear distance) to change to the adjacent lanes. The control effect can be improved in two aspects: the flexible eviction range and coordinated lane-changing cooperation between driven-away vehicles and neighboring vehicles. The flexible eviction range can control the number of lane-changing vehicles to an appropriate level, which reduces the interference with adjacent lanes. For example, in the bus lanes with intermittent priority (BLIP) method proposed by Eichler [14, 15], the bus lane space in front of the rear bus acts as the eviction range and uses variable message sign (VMS) or signals embedded in the road to guide the vehicles to change lanes. Dong divided the bus lane in the road section into smaller space slices as eviction units in the BLTDM method [5, 6]. Wu et al. [16] used real-time interactions of connected vehicles (CVs) to send eviction information to vehicles within a controlled range, which further improved the control accuracy of the eviction range. In addition, coordinated lane-changing cooperation can improve the success rate of lane-changing. Hao et al. [17], Xie et al. [18], and Ni et al. [19] applied CV technology to the cooperative lane-changing process. However, methods that discharge excessive vehicles to regular lanes are only suitable for unsaturated traffic. When the traffic is saturated, there is insufficient space for extra vehicles because the gap between vehicles in regular lanes is already very small. Furthermore, Zhu [20], Barria and Thajchayapong [21], and Zhang et al. [22] showed that forced lane changing in this situation is more likely to cause disturbances or even blockages of rear traffic in both lanes where the vehicles are leaving and entering; thus, even the use of CV technology can only improve the eviction effect to a certain extent.

Lane-borrowing vehicles can be accommodated in the lane space between a front and rear bus. When allowing as many regular vehicles as possible to borrow such space, it is required that all those vehicles do not cause additional delays to the rear bus. The total amount of vehicles that meet this requirement is called the capability of IBL utilization for regular vehicles (referred to as the capability of IBL). When the strategies are implemented without determining the capability of IBL in advance, either excessive lane-borrowing vehicles cause additional bus delays, or too few lane-borrowing vehicles result in reduced utilization of the bus lanes. Vladimir et al. [23] found through simulation experiments that IBL can only ensure that the bus delay does not increase significantly when the departure frequency of buses is low. Moreover, Qiu [24] reported that IBL can only significantly increase the speed of buses within a certain traffic density range, and the speed of traffic flow in a regular lane is unavoidably reduced. Wu [25] developed a three-lane cellular automata (CA) model of BLIP in CV environments; the simulation results showed that the BLIP strategy based on CV technology can only be applied to a traffic density of 30–90 pcu/km (passenger car units per kilometer) and a bus departure interval of greater than 90 s. Furthermore, it can only reduce, but not avoid, additional bus delays. In addition, a field trial of IBL was implemented in Lisbon, Portugal [4]. The results showed that the bus travel time was effectively reduced, but IBL is not appropriate for saturated traffic conditions [26]. Another similar trial and evaluation conducted in Melbourne, Australia, showed poorer results than those in Lisbon due to the high congestion and complex traffic environment [27]. Therefore, the most reliable method is to determine the capability of IBL before the implementation of the lane-borrowing strategy and allow vehicles within the capability range to borrow bus lanes.

The ideal situation of the control strategy is that the entire space between the front and rear buses is used for lane-borrowing vehicles, such that those vehicles and the two buses maintain a platoon formation. However, the complications caused by facilities such as signal lights and near-side stops in urban traffic can easily cause the platoon to lose its stability, leading to additional delays to the rear bus. Truong [9] reported that waiting at a red signal and a bus stopping at a near-side stop cause vehicles to join a traffic queue. When these two factors are superimposed, the situation becomes more complicated. For example, when a bus is about to arrive at a near-side stop, it may first join a traffic queue starting from the near-side stop in front, experience its own stay at the stop, join a traffic queue starting from the stop line caused by a red signal, and finally leave the road section at the time the light turns green. The delay of the rear bus is divided into two types: (1) the delay not related to the lane-borrowing vehicles such as waiting at a red signal or waiting behind the front bus at a red signal or near-side stop. (2) The delay caused by lane-borrowing vehicles. When these vehicles form a queue at a red signal or are hindered by a front bus that is waiting at a red signal or staying at a near-side stop, they are unable to leave and free the bus lane in time for the rear bus. The first type of delay can be improved by using the TSP and RSP methods, which were not considered in this study. The analysis of the second type of delay involves the phase of the signal lights, traffic capacity of the road section, driving status of the front bus, and changeable total amount of lane-borrowing vehicles in the bus lane. It is difficult to determine the second type of delay using simple parameters, such as the fixed-length buffer space or travel time of lane-borrowing vehicles. This explains why additional bus delays are unavoidable in the above control strategies.

To improve the adaptability of the IBL strategy under saturated traffic, we propose to determine the capability of IBL utilization for regular vehicles first, and then use it as the total amount restriction of lane-borrowing vehicles to
implement a bus lane control strategy. At the same time, a calculation model of the capability of IBL is established. This study provides a theoretical basis for the follow-up research of control strategy. To our knowledge, there is no research to propose a similar implementation path of bus lane control methods or clearly define the capability of IBL. The first step for determining the capability of IBL is establishing the basic control units. Subsequently, considering the influences of the phase of the signal light and the near-side bus stop, the kinematic wave theory and time-space diagram method are used to analyze the traffic evolution process of lane-borrowing vehicles and determine the capability of IBL that can make full use of the bus lane resources without hindering the buses.

The remainder of this paper is organized as follows. Section 2 establishes the traffic scene for the method, analyzes the evolution process of traffic flow formed by lane-borrowing vehicles and provides the calculation model. Section 3 details the evaluation of the proposed method through a traffic micro simulation software, and Section 4 summarizes the paper and presents the future scope.

2. Methods

The traffic scene is described in Subsection 2.1. The evolution of the mixed traffic flow composed of lane-borrowing vehicles and buses in the bus lane is analyzed using the time-space diagram method, which is then divided into two stages: the bus blocking stage and traffic light blocking stage, according to the driving state of the lane-borrowing traffic flow. Then, in Subsection 2.2, the calculation model of the capability of IBL is given according to the analysis results, and the model is further developed considering the influence of bus halts.

2.1. Traffic Scene. Figure 1 shows the schematic of a typical road section, including a bus lane (BusL) and main lane (MainL), which is in a near-saturated state, for the calculation of the capability of IBL. The main lane only shows the adjacent lane of the bus lane. Two adjacent buses in the front and rear, namely, the front bus \(B_f\) and rear bus \(B_r\), form a bus group \((B_f, B_r)\). The rear bus in this group is also the front bus in the latter group. The distance between two buses in one group is expressed by the time headway \(t_{pp}\) when they enter the road section. From the view of the road section, the available space for regular vehicles is the lane space between the buses in one bus group and limited by the length of the road section, which is defined as the basic unit. Correspondingly, the lane-borrowing process should be completed within the period from the time when \(B_f\) enters the road section to the time when \(B_r\) leaves the road section. Here, such period is called the lane-borrowing period.

Figure 2 depicts the time-space diagram of the evolution process of traffic flow in the bus lane, including the front bus \(B_f\), rear bus \(B_r\), and lane-borrowing vehicles. Here, the driving state of the bus has been simplified, that is, the bus travels at 0 speed when it stays at the stop or waits at the red signal, while it travels at a constant speed \(v_b\) the rest of the time. In addition, to accurately control the number of lane-borrowing vehicles, they are only allowed to enter the bus lane at the entrance of the road section. After \(B_f\) enters the bus lane of the current road section at the green signal, the passing-by regular vehicles that do not exceed the capability of IBL can start to enter the bus lane.

Because the number of vehicles that can enter the bus lane is based on the arrival traffic flow of the main lane during the lane-borrowing period, the arrival traffic flow must be determined first. When the front bus \(B_f\) enters the current road section at the green signal of the upstream traffic light, lane-borrowing vehicles arrive from the upstream main lane. During the red signal of the upstream traffic light, vehicles turn to the bus lane of this road section, and a similar arrival traffic flow as the upstream main lane can be achieved under saturated traffic. Therefore, we ignore the intermittent influence of the upstream signal on the traffic arrival flow. Thus, the arrival traffic flow is set to constant \(q_c\). The capability of IBL can then be expressed by \(Q = q_c \cdot t_{on}\), where \(t_{on}\) represents the open duration of the bus lane.

An analysis of the traffic evolution process of lane-borrowing vehicles is presented here. During the lane-borrowing period, vehicles are affected by two factors when forming a congested queue. Therefore, the evolution process was divided into two stages.

(1) In the first stage, congestion is caused by the slow-moving front bus \(B_f\), which can be called the bus blocking stage. This stage is defined as the time from the moment \(B_f\) enters the road section to the moment \(B_f\) leaves the downstream intersection. The time span of this stage is only related to the travel time of the front bus \(B_f\) on the road. The open duration in this stage is set as \(t_{on1}\). The control strategy of the bus lane is applicable only when the traffic saturation is high. Even if the speed of the traffic flow in the bus lane is lower than that of the main lane because of the slow front bus \(B_f\) (which acts as a bottleneck), there will still be adequate vehicles willing to enter the bus lane quickly. These vehicles then form a congested queue. Therefore, the vehicles move at a speed of \(v_b\), finally reaching the downstream intersection and forming a queue with a length of \(l\). This type of queue is also called a \(B_f\) fleet, as shown in Figure 1. In addition, the impact of bus stops on the evolution process must be considered. Bus stops are typically set up near downstream intersections to take advantage of the time when buses wait at a red signal to pick up and drop off passengers [28]. The impact of these near-side stops was analyzed. The variable \(\alpha = 1\) indicates that the bus will stop at the near-side stop; otherwise, the bus will ignore the stop.

(2) During the second stage, the lane-borrowing vehicles are only blocked by the red signal at the intersection and can only wait for the periodic green signal to leave the road section, which can be called the traffic light (TL) blocking stage. This stage is defined as the
Figure 1: Typical road section for calculating the capability of IBL.

Figure 2: Time-space diagram of two possible evolution processes of lane-borrowing traffic flow with different arrival signals and different traffic flow saturations in the road section. (a) Evolution process of two stages with green arrival signal \(0 \leq t_{offs} < \lambda_c\) and oversaturated traffic. (b) Evolution process of two stages with red arrival signal \(\lambda_c \leq t_{offs} < c\) and unsaturated traffic.
time from the moment the front bus \( B_f \) exits the downstream intersection to the moment the rear bus \( B_r \) arrives at the downstream intersection. The time span of this stage is related to the time headway of the two buses in the bus group. If the bus lane still has a spare space before the arrival of the rear bus, more vehicles can continue to enter the bus lane. The open duration at this stage is set as \( t_{on2} \). Therefore, for the road section, there are both entering and leaving vehicles at this time. After the bus lane is closed, no new vehicles enter and the remaining vehicles are gradually released at the intersection. When the traffic state of the intersection is saturated, the number of vehicles released in each signal period is less than the number of vehicles arriving. The traffic queue in front of the stop line gradually accumulates after every signal cycle and is then gradually released after the bus lane is closed, as shown in the second stage of Figure 2(a). In the unsaturated state, the accumulated queue for each red signal can be released in the next green signal, as shown in the second stage of Figure 2(b). Notably, once \( B_f \) leaves the current road section, the following vehicles can use the intersection space or turning behavior to choose a nonbus lane to drive, so their speed will no longer be affected by \( B_f \). It is also assumed that vehicles from the upstream bus lane cannot enter the downstream bus lane directly. They can continue to borrow the lane only according to the corresponding open state of the downstream bus lane (such as \( C_3 \) and \( C_4 \) in Figure 1). The purpose of this assumption is to allow all lane-borrowing vehicles to be controlled by the total amount of lane permitted for regular vehicles, which is adjusted according to the open period of the bus lane.

To ensure a fixed start time for the discharge capacity of the intersection in the second stage, the time demarcation point of the two stages is set at the end of the first encounter period \( C_0 \), which is defined as the signal period starting from the green phase when \( B_f \) arrives at the downstream intersection. Correspondingly, the offset between the starting time of \( C_0 \) and the arrival time of \( B_f \) is set to \( t_{offs} \). The signal period length is \( c \), and the time split is \( \lambda \), with the yellow time included in the red time. Regardless of how the traffic flow evolves in the first stage, the subsequent evolution process can be uniquely determined if the accumulated queue length \( l_f \) at the beginning of the second stage is estimated.

The bus blocking stage in Figure 2(a) shows that \( B_f \) encounters the green signal of the first encounter period \( C_0 \) (\( 0 \leq t_{offs} < \lambda c \)), and Figure 2(b) depicts that \( B_f \) encounters the red time (\( \lambda c \leq t_{offs} < c \)). Figure 2 shows only two possible combinations of different arrival offsets, \( t_{offs} \), and saturation states; the other combinations can also be easily obtained. Similarly, Figures 3(a) and 3(b) demonstrate the different arrival offsets under the influence of near-side stops. The blue line represents the bus staying at the stop. The distance from the near-side stop to the stop line is set as \( l_p \), and the dwelling time at the stop is set as \( t_p \).

The time-space diagram of the TL blocking stage when affected by a near-side stop can refer to the TL blocking stage in Figures 2(a) and 2(b) according to whether the traffic state is saturated; therefore, the time-space evolution diagram in Figure 3 omits the TL blocking stage (the impact of the near-side stop in the TL blocking stage will be analyzed in Subsection 2.2). Furthermore, if the front bus leaves the road section immediately when encountering the green signal (Figures 2(a) and 3(a)), some vehicles will also leave with it; this process is included in the bus blocking stage.

To reduce the disturbance of traffic flow caused by the frequent opening and closing of the bus lane, it is stipulated that in the control process of a basic unit (including one bus blocking stage and one TL blocking stage), the bus lane can only be opened once; that is, \( t_{on1} \) and \( t_{on2} \) are continuous opening periods, and the total duration is \( t_{on} = t_{on1} + t_{on2} \).

In the entire evolution process of the bus lane, if all the lane-borrowing vehicles do not want to hinder the rear bus, the last vehicle should always be driven in front of the rear bus. Because vehicles may be blocked in the process of driving and may form queue-forming and queue-discharging waves, the evolution process of the lane-borrowing traffic flow must be analyzed to determine whether the driving trajectory of the last vehicle conflicts with that of the rear bus \( B_r \). To this end, after defining the lane space of the section corresponding to the bus group \( (B_f, B_r) \) as the basic unit, the traffic discharging capacity of the bus lane is used as the estimated total amount of lane-borrowing vehicles, using the driving trajectory of the rear bus to limit the traffic queue length formed by those vehicles. Considering the impacts of the signal light phase and near-side bus stop on the queue length, the total amount of vehicles is corrected to the capability of the IBL for regular vehicles that can make full use of the bus lane space without hindering bus travel.

Kinematic wave theory [29, 30] was employed to study the velocity evolution law of lane-borrowing traffic flow. The other parameters, \( v_m, k_m, J \), and \( u_0 \), denote the free-flow speed, jam density, and congested shockwave speed, respectively. There are three different states: State \( S \) is the capacity state, where vehicles are discharged with saturation flow rate \( q_m \) and density \( k_m = q_m/v_m \). \( J \) is the jam state with zero flow rate and density \( k_J \). \( C \) is the state where the front bus \( B_f \) acts as a bottleneck to the following vehicles whose velocity is \( v_0 \), similar to \( B_f \), and the flow rate is the arrival traffic flow \( q_c \) and density \( k_c = q_c/v_c \). Using kinematic wave theory, when the \( B_f \) fleet is blocked by a traffic light, the queue dynamic can be described by queue-forming shockwave \( u_1 \) between states \( C \) and \( J \). Furthermore, when the \( B_f \) fleet discharges after \( B_f \) leaves the downstream intersection, it can be described by discharging shockwave \( u_2 \) between states \( C \) and \( S \). The speed of the shock waves can be expressed as follows:

\[
\begin{align*}
    u_1 &= \frac{q_c - 0}{k_c - k_J} = \frac{0 - q_m}{k_J - k_m}, \\
    u_2 &= \frac{0 - q_m}{k_J - k_m}.
\end{align*}
\]
2.2. Calculation Method for Capability of IBL

2.2.1. Time-Space Diagram Analysis of Lane-Borrowing Process. The previous analysis shows that the capability of each basic unit cannot exceed the discharging capacity of the intersection within the corresponding lane-borrowing period. Therefore, the evolution process of the lane-borrowing vehicles during the TL blocking stage must be analyzed first.

The following research assumes that some parameters of the buses have been obtained, including the real-time location, bus travel time in each downstream road section, dwelling time at the near-side stop, and arrival flow of the road section. This information is based on the prediction research of bus trajectory [31–33], bus dwelling time at the stop [34], and arrival traffic flow [35, 36].

The times when the front bus $B_f$ and rear bus $B_r$ enter the bus lane are $t_f$ and $t_r$, respectively; the time headway between the two buses is $t_{gap} = t_r - t_f$. The offset in the first encounter period $C_0$ of $B_f$ is $t_{off}$ when $B_f$ reaches the downstream intersection; thus, the TL blocking stage starts until the remaining duration $(c - t_{off})$ of $C_0$ is completed. The duration of this stage is expressed as

$$t_s = \max\left(t_{gap} - (c - t_{off}), 0\right),$$ (2)

where $t_s = 0$ indicates that the final time headway between the two buses is less than the remaining duration of $C_0$, and only the bus blocking stage exists in the evolution process. Therefore, the precondition for the existence of the TL blocking stage is $t_s > 0$.

Next, we analyze the discharging capacity of the intersection in the TL blocking stage and determine the constraints on the cumulative queue length $l_f$ at the initial stage. Let $m$ denote the number of complete signal cycles contained in the duration $t_s$, where $m = t_s / c$ ($\lfloor \cdot \rfloor$ is the rounding down function). When the last green signal begins before the rear
bus $B_s$ reaches the intersection, the rear position of the traffic queue formed by lane-borrowing vehicles is the key to ensuring that the rear bus is not hindered, which is determined by the queue-discharging shockwave $u_2$ and is denoted as $l_{r-max} = t_s - mc/(1/\nu_f) + (1/\nu_b)$. The lane-borrowing vehicles can discharge normally and will not hinder $B_s$, provided that the trajectories of the last vehicle in the queue and those of $B_s$ do not intersect. The corresponding discharging trajectory is shown as $\mathbb{O}$ in Figure 2(a). The length of the actual discharging queue $l_r$ is constrained by $l_{r-max}$ or $l_r \leq l_{r-max}$. However, if the queue with length $l_r$ cannot discharge completely in this green signal and is obstructed by the following red signal, $B_s$ will be hindered. Therefore, $l_r$ is limited by the queue length $l_f = \lambda c/1/\nu_f + 1/\nu_b$, which denotes the maximum queue length that can be discharged in one green signal; otherwise, the remaining vehicles can only leave at the next green signal, hindering $B_s$. The corresponding discharging trajectory is shown as $\mathbb{O}$ in Figure 2(a). According to this analysis, $l_r$ can be expressed as $l_r = \min(l_{r-max}, l_f)$. Thus, the discharging capacity represented by the length of the blocking queue in front of the stop line can be written as

$$l_{d-max} = m \cdot l_d + l_r,$$  \hfill (3)

where $m \cdot l_d$ is the queue length that discharges over all the complete signal cycles.

The discharging capacity represented by the queue length $l_{d-max}$ is shared by the lane-borrowing vehicles in the two stages, that is, the vehicles that enter the duration $t_{on1}$ of the bus blocking stage, which form a queue with the length $l_f$, and those that enter when the discharging capacity of the TL blocking stage is still in surplus, and the bus lane continues to be opened for duration $t_{on2}$. Considering that the total amount $Q$ of all lane-borrowing vehicles in the two stages does not exceed the discharging capacity of the intersection, we have

$$Q = l_f k_f + t_{on2} q_c \leq l_{d-max} k_f = (m \cdot l_d + l_r) k_f.$$ \hfill (4)

In addition, the traffic queue length in the bus blocking stage is subject to another constraint. If the front bus $B_f$ encounters the green signal when reaching the downstream intersection (Figure 2(a)), it can immediately leave the road section, and the following vehicles also start to leave. However, if too many vehicles follow $B_f$, the remaining vehicles will form a shorter queue with maximum possible length $l_m = (1 - \lambda) c/1/\nu_i - 1/\nu_i$ when blocked by the following red signal. If $B_f$ encounters the red signal (Figure 2(b)), the following vehicles can enter the TL blocking stage after the red signal ($c - t_{ofs}$) is completed. The maximum possible length $l_m$ of the accumulated queue corresponds to the remaining red signal ($c - t_{ofs}$) of the first encounter period $C_0$, that is, $l_m = c - t_{ofs}/1/\nu_i - 1/\nu_i$.

To continue to use the bus lane space in the TL blocking stage, where $t_{on2} > 0$, according to the constraint that the bus lane can only be opened once, the final queue length in the bus blocking stage must satisfy the condition $l_f = l_m$ to ensure that duration $t_{on2}$ is a continuation of duration $t_{on1}$. According to equation (4), $t_{on2} \leq (m \cdot l_d + l_r - l_f) \cdot k_f/q_c$. In this case, the evolution process of the lane-borrowing vehicles completes two stages, and the conditions that should be met can be grouped as

$$\left\{ \begin{array}{l} l_f = l_m \\ 0 < t_{on2} \leq (m \cdot l_d + l_r - l_f) \cdot k_f/q_c \end{array} \right.$$ \hfill (5)

However, if the final possible maximum queue in the bus blocking stage exceeds the previously obtained intersection discharge capacity, which is represented by $l_{m} > l_{d-max}$, there must be a relationship $l_f < l_m$ because the actual final queue length $l_f$ in the bus blocking stage must be less than the intersection discharge capacity $l_{d-max}$, namely, $l_f \leq l_{d-max}$. This also means that there is no space left in the TL blocking stage to support the continued opening of the bus lane, that is, $t_{on2} = 0$. In this situation, the entire discharging capacity is used for the accumulated queue in the bus blocking stage. The conditions that should be satisfied can be grouped as follows:

$$\left\{ \begin{array}{l} l_f = l_{d-max} < l_m \\ t_{on2} = 0 \end{array} \right.$$ \hfill (6)

After meeting the conditions in equations (5) and (6), the opening duration of the bus blocking stage is obtained as

$$t_{on1} = l_f \left( \frac{1}{\nu_b} - \frac{1}{\nu_i} \right) + \max(\lambda c - t_{ofs}, 0).$$ \hfill (7)

The second term on the right-hand side of the equation is equal to the remaining green signal in the first encounter period, $C_0$. Vehicles entering at this time correspond to those that leave the intersection immediately after $B_f$ leaves, as mentioned earlier.

These cases assume that the discharging capacity of the intersection exceeds zero in the TL blocking stage. However, if the intersection has no discharge capacity, namely, $t_s = 0$, there is no TL blocking stage in the evolution process, which implies $t_{on2} = 0$. Furthermore, some lane-borrowing vehicles can leave in the bus blocking stage only when $B_f$ encounters a green signal at the intersection, and the bus lane is opened for a duration of $t_{on1} = \lambda c - t_{ofs}$. In contrast, when it encounters a red signal, no vehicles can enter the bus lane, and $t_{on1} = 0$. The conditions for this situation can be grouped as follows:

$$\left\{ \begin{array}{l} l_f = l_{d-max} = 0 \\ t_{on2} = 0 \\ t_{on1} = \max(\lambda c - t_{ofs}, 0) \end{array} \right.$$ \hfill (8)

In addition, the constraint of the length of the road section on the length of the lane-borrowing traffic queue during the accumulation process must be considered. In the bus blocking stage, the final queue length $l_f$ is the maximum accumulated queue length, which must be less than the maximum possible accumulated queue length, that is, $l_f \leq l_m$. Moreover, $l_m$ will not exceed the
accumulated queue length in one red signal, $l_f$ is much smaller than the length of the road section. Hence, the constraint of the section length is satisfied. In the TL blocking stage, if the arrival traffic flow is unsaturated, the queue accumulated during each red signal can be discharged in one green signal, thus fulfilling the constraint.

However, under saturated traffic conditions, the discharge capacity of one signal cycle cannot fully release the traffic flow arriving in the same period. That is, the accumulated queue length $l_a$ during the red signal in a signal cycle is not less than the queue length $l_f$ that can discharge during the green signal, where $l_a = (1 - \lambda)c/1/u_1 - 1/ut_2$. Then, within the open duration $t_{on2}$, the queue with the initial length $l_f$ will grow in length during each complete signal cycle with $(l_a - l_f)$. Let $t_c = l_a/(1/u_1 + 1/v_{pm})$ represent the opening duration required to form the queue length $l_a$; then, after each opening period $t_c$ is completed, the intersection of shockwaves $u_1$ and $u_2$ is the periodic longest state of the queue, as shown by point b in Figure 2(a). When the opening period is incomplete, the longest state is shown at point c. If the number of complete opening periods $t_c$ in the TL blocking stage is $N$, where $N = t_{on2}/t_c$, the opening duration is corrected to form the queue length $l_a$; then, after each opening period $t_c$ is completed, the intersection of shockwaves $u_1$ and $u_2$ is the periodic longest state of the queue, as shown by point b in Figure 2(a). When the opening period is incomplete, the longest state is shown at point c. If the number of complete opening periods $t_c$ in the TL blocking stage is $N$, where $N = t_{on2}/t_c$, the opening duration is corrected to form the queue length $l_a$; then, after each opening period $t_c$ is completed, the intersection of shockwaves $u_1$ and $u_2$ is the periodic longest state of the queue, as shown by point b in Figure 2(a). When the opening period is incomplete, the longest state is shown at point c. If the number of complete opening periods $t_c$ in the TL blocking stage is $N$, where $N = t_{on2}/t_c$, the opening duration is corrected to

\[
\begin{align*}
I_{N-1} & = I_f + (N - 1) \cdot (l_a - l_f) \leq L (i), \\
I_N & = \left[ l_f \cdot k_j + t_{on2} \cdot q_c - (N - 1) \cdot l_a \cdot k_j \right]/k_j \leq L (ii).
\end{align*}
\]

If $t_{on2}$ satisfies Equation (9), it can be used as the actual opening duration. However, if any of the requirements in Equation (9) are not met, $N \leq L - l_f/l_a - l_d + 1$ can be obtained from Equation ((9)(ii)). Taking positive integer values from large to small within the range of $N$, the first value that satisfies the constraint of (9)(ii) is obtained, namely, $N'$. Subsequently, the actual opening duration is corrected to

\[
t_{on2} = \left[ L - l_f + (N' - 1)l_d/k_j \right]/q_c.
\]

Finally, according to the arrival traffic flow $q_c$, the capability of IBL is calculated as

\[
Q = q_c(t_{on1} + t_{on2}) = q_c t_{on}.
\]

2.2.2. Impact of Near-Side Bus Stop. This subsection considers the impact of near-side stops on the capability of IBL. First, the difference between the impacts of the front and rear buses was analyzed. When the rear bus $B_r$ stops, the distance between $B_r$ and the queue in front will increase; that is, the queue in front will receive an additional discharging time equal to the stop time. However, if the near-side stop is closer to the intersection, this additional discharging time is reduced when the queue is blocked by the red signal at the intersection. In this scenario, the remaining space is compressed again and is insufficient to accommodate more vehicles; therefore, such extra space caused by $B_r$ halts will not be considered.

When $B_f$ stops, a traffic queue is formed behind the bus. While $B_f$ is still moving forward, it compresses the time headway between the two buses during the bus blocking stage. The time-space diagram shows that when the time headway between the two buses is relatively large, the queue formed by the halt of $B_f$ at the near-side stop does not hinder $B_r$. The halt of $B_f$ will only delay the lane-borrowing vehicles at the near-side stop for a period and will affect the evolution process in the bus blocking stage, but not the capability of IBL. However, when the headway time is relatively small (less than one signal period), the traffic queue behind the near-side stop may hinder $B_r$. At this time, it is necessary to restrict the opening duration to reduce the number of lane-borrowing vehicles and ensure sufficient space in front of $B_r$.

First, the duration of the TL blocking stage $t'_r$ is estimated when $B_f$ stops at the near-side stop, and the impact of the lane-borrowing traffic queue is not considered. In this case, the time headway between the two buses at the downstream intersection is $t_{gap} = \max(t_f - t_f - at_p, 0)$, where $at_p$ represents the dwelling time of $B_f$ at the near-side stop. If $t_{gap} = 0$, the time headway is so small that $B_f$ is overtaken by $B_r$ in the process of stopping, leaving no space for any lane-borrowing vehicles. Considering the influence of the remaining time $(c - t_{ofr})$ of the first encounter period $C_0$, the estimated duration of the TL blocking stage can be obtained as

\[
t'_r = \max(t_r - t_f - at_p - (c - t_{ofr}), 0).
\]

Accordingly, the estimated length-represented discharge capacity $l_{d-max}$ of the intersection in the bus lane can be obtained using Equation (3).

Next, the constraint of the trajectory of the rear bus $B_r$ on the length of the lane-borrowing traffic queue is considered in the bus blocking stage. The cumulative queue length $l_f$ at the end of the bus blocking stage is used as the estimated queue length in stop mode without considering the impact of the near-side stop on the traffic queue. The following method is implemented to determine whether the cumulative traffic queue with length $l_f'$ hinders $B_r$. Calculate two trajectories: one is of the last vehicle in the estimated lane-borrowing traffic queue when the queue is blocked by the halt of the front bus $B_f$ at the near-side stop, and the other is of $B_r$ when it drives from the entrance to the near-side stop. If the two trajectories intersect, $B_r$ catches up with the last vehicle when the vehicle stops, and there are an excessive number of vehicles that hinder $B_r$ in the estimated queue with length $l_f'$. It is necessary to consider the trajectory of $B_r$ as the constraint to $l_f'$. In addition, the following conditions should be considered when selecting the trajectory of $B_r$ as a constraint: the vehicle ahead of $B_r$ must be able to discharge at the last green signal before $B_r$ reaches the stop line, so as not to obstruct $B_r$ while waiting for the next red signal, as shown in Figure 3(c). Therefore, if $B_r$ arrives at the red signal (the time headway condition is $\lambda c < t'_r < c$, shown as trajectory $B_r(1)$), its trajectory should be replaced by another $B_r$ trajectory that just left the road section at the end of the green signal (denoted as trajectory $B_r(2)$). Conversely, if $B_r$
arrives at the green signal (the time headway condition is $0 \leq t_{f}' \leq \lambda t$), the actual trajectory of $B_s$ is used. Subsequently, the relationship between the following three parameters is determined (Figure 3) as follows:

1. Maximum possible length $l_1$ of traffic queue behind the near-side stop:
   
   $$ l_1 = \frac{t_p}{1/u_1 - 1/u_2}. $$

2. Equivalent queue length $l_2$ at the near-side stop of the estimated traffic queue length $l_f'$, which accumulates at the intersection when the near-side stop is not considered:
   
   $$ l_2 = \frac{1}{u_1 + 1/v_b} \left[ l_f' \left( 1/u_1 + 1/v_b \right) + \lambda c - t_{offs} + t_p(1/v_b + 1/u_2) \right] - l_p. $$

3. Distance $l_3$ from $B_s$ to the near-side stop when $B_s$ is not hindered by the traffic queue accumulated at the near-side stop:
   
   $$ l_3 = \min \left( t_s', \lambda c \right) + c - t_{offs} + t_p \left( 1/v_b + 1/u_2 \right) - l_p, \left( t_s' \leq c \right). $$

Moreover, $l_2 \leq l_3$ when the discharging of the estimated queue $l_f'$, which accumulates at the intersection, does not hinder the rear bus $B_s$. Accordingly, we present the following conditions:

1. When $l_1 \leq l_2 \leq l_3$, or $l_2 \leq l_1 \leq l_3$, as shown in Figures 3(a) and 3(b), the estimated intersection queue $l_f'$ does not affect the driving of $B_s$ when the queue is blocked at the near-side stop. It can be used as the actual cumulative queue length $l_f$ at the intersection, that is, $l_f = l_f'$. According to the definition of the stages, the opening duration of the first and second stages will be different in the two cases. Because some lane-borrowing vehicles are blocked by the traffic queue, the opening duration $t_{on1}$ of the bus blocking stage in condition $l_2 \leq l_1 \leq l_3$ is smaller than that in condition $l_1 \leq l_2 \leq l_3$, and the opposite is true in the TL blocking stage. Meanwhile, the total opening duration $t_{on}$ remains unchanged. Therefore, the opening duration is calculated according to condition $l_1 \leq l_2 \leq l_3$. Hence, $t_{on1}$ can be obtained by
   
   $$ t_{on1} = l_f \left( \frac{1}{u_1} + \frac{1}{v_b} \right) + \max \left( \lambda c - t_{offs}, 0 \right) + t_p. $$

Similarly, $t_{on2}$ can be obtained when the bus is not halted at the near-side stop by using either equation (5) or (6). The result of $t_{on}$ also shows that when the bus stops, as long as the traffic queue does not hinder the rear bus $B_s$, the near-side stop does not affect the capability of IBL.

2. Under the condition $l_2 \leq l_3 \leq l_1$, as shown in Figure 3(c), the estimated cumulative queue with length $l_f'$ hinders $B_s$ during the previous blocked process caused by $B_f$ at the near-side stop. It is necessary to restrict $B_s$'s trajectory to reduce the opening duration and thereby prevent excessive lane-borrowing vehicles from entering the bus lane. At this time, the opening durations $t_{on1}$ and $t_{on2}$ of the two stages are not strictly distinguished; however, the total opening duration $t_{on}$ is directly determined:
   
   $$ t_{on} = l_f \left( \frac{1}{v_b} + \frac{1}{u_1} \right). $$

Finally, when the duration of the TL blocking stage $t_s = 0$ is similar to that when there is no near-side stop (explained in Subsection 2.2.1), the opening duration in the bus blocking stage is $t_{on} = \lambda c - t_{offs}$ when $B_f$ encounters the green signal at the intersection.

The capability of IBL can be calculated using equation (10).

3. Experiment and Results

The main purpose of providing a bus lane control strategy is to reduce the congestion of regular traffic, without causing additional bus delays, after a lane in the road section is dedicated to buses. The proposed calculation method of the capability of IBL estimates the total amount of lane-borrowing vehicles in advance to ensure the smooth implementation of the bus lane control strategy. In this section, we use a simulation software, Simulation of Urban MObility (SUMO) [37], to evaluate the performance of the proposed method when the three influencing factors of the traffic state change, namely, the bus departure interval, traffic saturation of the regular lane, and whether the bus stops or not. The process takes the obtained capability of the bus lane as the total amount of lane-borrowing vehicles (referred to as IBL with capability, IBL-C) and then analyses the average travel time of buses and regular vehicles and the traffic capacity of the road section. The applicable conditions of the method are discussed and compared with the existing control strategies IBL and DBL, which do not consider the capability of the bus lane.

3.1. Experimental Setup. A three-lane road section with length $L = 800m$ is built, with the right-side lane as the bus lane and the other two as regular lanes. The saturated flow of a single lane is set as $d_m = 1800veh/h/lan$ when the influence of signal lights is not considered; the traffic capacity of a single lane is $N_m = \lambda d_m$. When the bus lane can be borrowed, the arrival traffic flow of the road section enters the bus lane with a probability of 1/3. The total amount of lane-borrowing vehicles constrained by the capability $Q$ can be controlled by the opening duration $T = Q/(2/3)q_c$, where $q_c$ denotes the arrival traffic flow in each regular lane. When the bus lane is closed, no traffic flow enters the bus lane. The ratio of the actual arrival traffic flow of the road section to the
regular three-lane traffic capacity is considered as the traffic flow saturation \( S \). Two-phase signal lights with time-split \( \lambda = 0.5 \) and period \( c = 100 \text{s} \) are set at the downstream intersection to reflect the intermittent traffic flow phenomenon in urban traffic. No signal lights are installed upstream of the road section. Table 1 lists the remaining parameters used in this study.

A program was developed using TRAFFIC Control Interface (TRACI) in SUMO to simulate the above scenarios. The simulation time of each scenario was adjusted with the distance between the front and rear buses to ensure that 200 sets of analysis data could be obtained for each bus group \( (B_f, B_r) \).

### 3.2. Results and Discussion

#### 3.2.1. Adaptability Analysis of the Method

Figures 4–6 show the average travel time of buses, average travel time of regular vehicles, and traffic flow volume of the road section in the three cases, under different traffic saturation and bus departure interval conditions, respectively. To simplify, all the traffic flow volume is normalized with the traffic capacity of the road section, which is 2700 veh/h in this study when \( S = 1 \). The average travel time of buses is used to determine whether there is additional bus delay, and the average travel time of regular vehicles and traffic flow volume of the road section are used to evaluate whether the congestion of regular traffic is reduced.

The average travel time of buses (Figure 4) shows that IBL-C is consistent with DBL, that is, bus travel is not disturbed under various traffic conditions. This is because the rear bus trajectory is used as a length constraint in the calculation of capability of IBL, which limits the total amount of lane-borrowing vehicles. However, in IBL, because there is no control over the lane-borrowing volume, the excessive lane-borrowing vehicles stay on the bus lane and induce additional delay to bus travel. Moreover, the delays increase when the saturation is high and departure interval is short. When the saturation \( S = 1.2 \), the bus departure interval \( t_{gap} = 150 \text{s} \), and the average traffic time increases by 23.6\% compared with IBL-C and DBL. When the saturation \( S \geq 1 \), the bus departure interval is between \([100 \text{s}, 250 \text{s}]\), and the average bus travel time exceeds that of the DBL by more than 10\%. The additional bus delay in the IBL can only be reduced when the bus departure interval is large. As the time headway of the front and rear buses increases, there are more opportunities for excessive vehicles that may be stranded in front of the bus to leave the bus lanes, such as finding available gaps in adjacent lanes for lane changing, using intersection space to access nonbus lanes downstream, or simply relying on the traffic capacity of the intersection.

Next, we consider the congestion situation of regular traffic flow. As shown in Figures 5 and 6, when the saturation is \( S \leq 0.8 \), the difference in average travel time of regular vehicles and traffic flow volume of the road section are negligible in the three cases, which is reasonable. This implies that when the traffic flow is light, no special control strategy is required for bus lanes. During \( S > 0.8 \), in DBL, after a lane is dedicated to buses, the actual traffic flow volume of the road section decreases. Therefore, the road section enters a saturated state and the travel time of regular vehicles increases rapidly. When \( S > 1 \), the two regular lanes can no longer accommodate more traffic, and the maximum value is the upper capacity limit of the section; therefore, the travel time no longer increases. In the other two cases, IBL-C and IBL, by allowing some vehicles to use idle resources of

### Table 1: Experimental simulation parameters.

| Parameters                                   | Value         |
|----------------------------------------------|---------------|
| Free flow velocity, \( v_m \)                | 18.68 m/s     |
| Bus velocity, \( v_0 \)                      | 13.89 m/s     |
| Jam density, \( k_f \)                       | 0.133 veh/m   |
| Distance from the near-side bus stop to the stop line, \( t_p \) | 80 m          |
| Dwelling time at the near-side stop, \( t_p \) | 20 s          |
| Bus departure interval, \( t_{gap} \)        | 50 – 450 s    |
| Traffic flow saturation \( S \)              | 0.5 – 1.2     |

![Figure 4: Bus average travel time.](image)

![Figure 5: Regular vehicle average travel time.](image)
the bus lane, the average travel time of regular vehicles decreases significantly, compared to that of DBL. When \( S \leq 1.1 \) and the bus departure interval \( t_{gap} > 150s \), the average travel time of regular vehicles and traffic flow volume are equal in the two cases.

There are two special cases. First, when the bus departure interval is \( t_{gap} \leq 100s \) and saturation interval is \( S > 0.9 \), the average travel time of regular vehicles in IBL-C is much smaller than that in IBL, and the corresponding traffic flow volume is larger than that in IBL, which is still close to the traffic capacity of three regular lanes. This is because, when the departure interval is relatively small, even if there is no influence of lane-borrowing vehicles, the rear bus \( B_r \) may be hindered by the front bus \( B_f \), which stops at the red signal. In the case of unknown downstream obstacles, the IBL adopts a larger fixed buffer space, for example, an entire section length, to prohibit vehicles from borrowing the bus lane, which can reduce additional delays to the rear bus. However, a possible excessive reduction in the number of lane-borrowing vehicles will reduce the utilization of the bus lane and further increase the average travel time of regular vehicles and decrease the traffic flow volume, as shown in Figures 5 and 6. The IBL-C considers the queuing factors that may be caused by the front bus, and therefore can make full use of the remaining space between the two buses when the front bus does not obstruct the rear bus. This also improves the adaptability of the method to high-density bus flow.

In another case, when the bus departure interval is \( t_{gap} \geq 200s \) and the saturation is \( S = 1.2 \), the average travel time of regular vehicles in IBL-C is increased by 36.5% compared with that in IBL, and the traffic flow volume is slightly lower than that in IBL. Although, within this range, IBL-C can improve road congestion less than IBL, it ensures that the average travel time of the bus does not increase, which is an improvement over IBL, as shown in the analysis of Figure 4. Such a phenomenon also occurs at low saturation; however, the difference between the two cases is not as noticeable. In other words, IBL-C based on the lane-borrowing volume can improve the traffic flow volume of the road section under the premise of ensuring bus priority, which is more in line with the original goal of bus lane control than the IBL strategy. The above analysis also shows that the IBL strategy can only significantly improve traffic flow volume under the condition of limited traffic saturation range and large bus departure interval, and it also inevitably increases bus delays, which is consistent with the conclusions of Vladimir [22] and Qiu [23]. Therefore, the IBL-C has a stronger adaptability to traffic saturation and bus departure intervals than the IBL.

Because there are multiple bus lines in urban traffic, the interval between the two buses in the front and rear is randomly changed. Figures 7–9 depict the average travel time of the buses, average travel time of regular vehicles, and average traffic flow volume, respectively, when the bus interval is random. As shown, the average travel time of buses is guaranteed in IBL-C. The travel time of regular vehicles gradually increases when \( S \leq 1.1 \) and \( S \) gradually increases, and the maximum amplitude is 18.3% of the free travel time. When \( S > 1.1 \), the regular vehicle travel time increases quickly because the arrival traffic flow is gradually over-saturated in all three lanes. In DBL, the bus does not have additional delays, but the travel time of regular vehicles rapidly increases owing to a large decrease in the traffic capacity of the road section after one lane is dedicated to buses. In the IBL, although the average travel time of regular vehicles is reduced by 25.9% compared with IBL-C, the average travel time of buses increases by 32.7%. In other words, in IBL-C, public transport always has a higher priority than regular vehicles.

Although there is a large difference in the average travel time of the buses and regular vehicles between IBL-C and IBL when the bus interval is random, the difference in traffic flow volume of the road section in these two cases is negligible. However, in DBL, traffic flow volume is limited to a certain level owing to the loss of a regular lane.

3.2.2 Influence Analysis of Near-Side Bus Stop. Figures 10–12 show the average travel times of buses and regular vehicles, and the traffic flow volume with a near-side bus stop in the section, respectively. By comparing with the results of IBL-C when there is no near-side stop (Figures 4–6), it can be found that:

1. The average travel time of the bus when it stops at the near-side stop increases by an average of approximately 27 s. In addition to the stop time, another reason for time loss is the speed change of the bus when it enters and exits the near-side stop. Such delays do not belong to the delays caused by lane-borrowing vehicles. Because the prior capacity estimate is performed, the average bus travel time in the IBL-C is the same as that in the DBL. However, if the total amount of lane-borrowing vehicles is not controlled within a proper range, the obstacles of excess vehicles on the rear bus are further enlarged because the space between the buses is further reduced when the bus stops, particularly at high saturation, as in the IBL shown in Figure 10. When \( S = 1.2 \), the average bus travel time is increased by

\[
\begin{align*}
\text{Figure 6: Traffic flow volume of road section.}
\end{align*}
\]
37.6% compared to those of the DBL and IBL-C, and the highest increase is 81.5%. The situation can be improved only after the interval between buses exceeds a certain range, referred to as \( t_{gap} \geq 400 \) s here. In such an interval, even if the traffic queue fills the bus lane, it can be discharged before the arrival of the rear bus; thus, the bus average travel time can be restored to the same value as in the other two cases. This is also the reason why the IBL strategy is not suitable for smaller bus departure intervals.

(2) In IBL-C, the near-side stop has a significant impact on the average travel time of regular vehicles only when saturation is high. Compared with the situation without near-side stops during \( S > 1 \), the average travel time is increased by an average of 53.1%. This is because, when the lane is saturated, the congested shockwave caused by near-side stops is rapidly transmitted upstream, expanding the scope of influence. However, when saturation is low, near-side stops only cause additional delays to a small number of lane-borrowing vehicles, which has a limited impact on the average travel time of regular vehicles. Conversely, in IBL, at the high saturation and large-departure interval, the value of the bus average travel time is greatly increased owing to the near-side stops, and the maximum travel time in various situations is increased from 85.5 s to 175.6 s. Under the same conditions of bus departure interval \( t_{gap} \geq 200 \) s and traffic saturation \( S = 1.2 \), when the bus does not halt at the stop, the average travel time of regular vehicles in IBL-C is increased by 36.5% compared with
traditional IBL, as obtained previously. Meanwhile, when the bus stops, this value is only 3.5%. In this regard, the advantages of traditional IBL are significantly reduced in the case where the bus stops.

(3) In the three cases, the impact of near-side stops on traffic flow volume is similar to that when there are no stops and only slightly reduces the traffic flow volume at high saturation and low departure intervals. This also shows that in the overall situation, the near-side stop only delays the driving process of the vehicles and does not affect the traffic capacity of the road.

These results show that when the saturation is high, the near-side stop causes a significant reduction in the capability
of IBL-C, resulting in a rapid increase in the average travel time of regular vehicles. However, its performance continues to be better than that of the IBL.

Figures 13 and 14 show the average travel times of buses and regular vehicles, respectively, when there are near-side stops and the bus departure interval is random. In IBL-C, compared with Figures 7 and 8, except for the increase in bus travel time due to near-side stops, the average travel time of regular vehicles does not change significantly; this is due to the reasonable estimation of the capability of IBL, and the lane space can still be fully utilized. In IBL, the change in performance is negligible at low saturation. However, at high saturation, the additional delays to the rear bus and the average travel time of regular vehicles both increase. This is because the phenomenon of excessive lane-borrowing vehicles is more evident, and the average distance between the front and rear buses decreases because the front bus stops. Furthermore, compared with IBL-C, the average travel times of the bus and regular vehicles increases by 58.1% and 5.0%, respectively. Hence, IBL-C has better adaptability to near-side stops than IBL. Figure 15 shows the average traffic flow volume is almost unchanged compared with Figure 9, which is consistent with the conclusion from Figure 12.

3.2.3. Traffic Time-Space Diagram. Figure 16 shows a time-space diagram of traffic flow in the bus lane in IBL-C. The bus interval is random, the arrival traffic flow per regular lane $q_c = 1350$ veh/lane/h, the thick blue lines represent the bus trajectory, and the orange lines represent regular vehicles trajectories.

In IBL-C, when the bus enters the bus lane, regular vehicles immediately follow and form a fleet after the bus, and the driving speed is limited by the bus speed. When the bus waits at the red signal at the intersection (Figures 16(a) and 16(b)) or halts at the near-side stop (Figure 16(b)), the bus fleet forms a blocking queue. When the rear bus reaches an intersection or near-side stop, the blocked queues must be completely discharged. Otherwise, even if there is free space in front of the bus, no regular vehicles can enter the bus lane. As depicted in Figure 16(a), the first bus arrives at the intersection during the red signal, and a small amount of space is abandoned to avoid being hindered by the traffic queue ahead. The second bus encounters a green signal, and the front traffic queue is discharged with a green signal, enabling the bus to pass through the intersection. Figure 16(b) shows that the traffic queue caused by the near-side stop discharges before the rear bus arrives at the near-side stop; thus, the rear bus enters the stop smoothly.

Furthermore, as the evolution process of the traffic flow of regular vehicles is considered, the traffic queue caused by the front bus does not hinder the rear bus, regardless of whether the front bus waits at a red signal or stops at the near-side stop.

4. Conclusions

To meet the needs of bus lane control under different traffic conditions, especially saturated traffic, we proposed the implementation path of a bus lane control method that determines the capability of IBL utilization for regular vehicles first, and then takes it as the total amount restriction of lane-borrowing vehicles. At the same time, a calculation model of the capability of IBL is established. The general concept is to divide the bus lane into basic lane-borrowing units, defined as the space between the front and rear buses of a bus group bounded by the length of the road section; estimate the total amount of lane-borrowing vehicles by the traffic discharging capacity of every unit; furthermore,
The results are summarized as follows:

(1) Allowing vehicles within the capability of IBL to borrow the bus lane to drive will not increase the travel time of the bus under any traffic saturation or bus departure interval conditions. No vehicles are required to move to the adjacent lane, and there is no traffic disturbance.

(2) For IBL-C, which considers the capability of IBL as the limitation number of the lane-borrowing vehicles permitted into the IBL, when the traffic state is saturated and the bus departure interval is relatively large, although the average travel time of regular vehicles is greater than IBL and its traffic flow volume on the road section is slightly smaller than IBL, it ensures that the bus is not hindered and has a stronger bus priority guarantee capability than IBL.

(3) When the traffic state is saturated and the bus departure interval is relatively small, the average travel time of regular vehicles in IBL-C is much smaller than that of IBL because the calculation method of the capability of IBL can adapt to small and changing bus departure intervals to fully utilize the bus lane resources.

(4) The calculation method also considers the influence of near-side stops and avoids additional obstruction of the rear buses caused by such factors.

(5) The traditional IBL can improve the traffic capacity of the road. However, due to the extensive control, the bus will be hindered and the method will fail in saturated traffic. When the amount of lane-borrowing vehicles is restricted by the capability of IBL, it is ensured that the bus will not be hindered, even if the traffic is saturated. Regardless of the bus spacing and whether the bus halts, the traffic capacity of the bus lane can be greatly improved.

As a creative path of bus lane resource utilization, there is still much work to be done to apply this method in the control strategy. For example, it is necessary to study the influence of bus trajectory prediction accuracy, coordination of control of multiple sections, etc. In addition, factors such as the success rate and degree of interference of forcing excess vehicles into adjacent lanes must be further investigated, and a discharging method must be introduced into the calculation method to enlarge the application range of the method.

**Notations**

- $t_{on}$: Open duration of the bus lane, and the opening duration of the bus blocking stage and traffic light blocking stage, respectively.
- $C_{0}$: Capability of IBL permitted for regular vehicles
- $t_{offs}$: First encounter period and corresponding offset that $B_f$ arrives at downstream intersection
- $c$, $h$: Length and time split of signal period
- $v_{m}$, $q_{m}$, $k_{m}$: Free-flow speed, flow rate, and density of the capacity state $S$
- $v_{b}$: Speed of bus
- $q_{c}$, $k_{c}$: Flow rate and density of state $C$ where the front bus $B_f$ acts as a bottleneck
- $u_{1}, u_{2}$: Speed of queue-forming shockwave and congested shockwave
- $k_{s}$: Jam density of state $J$
- $t_{gap}$: Time headway between $B_f$ and $B_r$ when $B_f$ enters the bus lane
- $t_{f}$, $t_{r}$: Time when $B_f$ and $B_r$ enter the bus lane
- $t_{s}$: Duration of TL blocking stage at the downstream intersection
- $m$: Number of complete signal cycles contained in $t_{s}$
- $l_{d-max}$: Discharging capacity represented by the length of the blocking queue in front of the stop line
- $l_{m}$: Maximum possible queue length that accumulated in red signal of $C_0$
- $l_{f}$: Accumulated queue length at the beginning of TL blocking stage
- $l_{d}$: Maximum queue length that can be discharged in one green signal
- $l_{a}$, $t_{c}$: Accumulated queue length during the red signal in a signal cycle and opening duration required in TL blocking stage
- $l_{r-max}$, $l_{r}$: Maximum possible length and actual one of discharging queue in the last green signal of TL blocking stage
- $l_{N-1}$, $l_{N}$: The longest queue lengths of the $(N - 1)$th and $N$th periods when traffic queue is accumulated in the TL blocking stage
- $l_{1}$: Maximum possible queue length behind the near-side stop
- $l_{2}$: Equivalent queue length at the near-side stop of the estimated traffic queue length $l_{f}$, which accumulates at the intersection when the near-side stop is not considered
- $l_{3}$: Distance from $B_r$ to the near-side stop when $B_r$ is not hindered by the traffic queue accumulated at the near-side stop.

**Data Availability**

The data used to support the findings of this study are available from the corresponding authors upon request.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.
Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant no. 61773347) and the Natural Science Foundation of Zhejiang Province (grant no. LY19E050008).

References

[1] H. S. Levinson and K. R. Jacques, “Bus lane capacity revisited,” Transportation Research Record: Journal of the Transportation Research Board, vol. 1618, no. 1, pp. 189–199, 1998.

[2] J. Viegas, “Turn of the century, survival of the compact city, revival of public transport,” in Transforming the Port and Transportation Business 51–63, H. Meersman and E. Van de Voorde, Eds., Uitgeverij Acco, Antwerp, Belgium, 1997.

[3] J. Viegas and B. Lu, “The Intermittent Bus Lane System: Demonstration in Lisbon,” in Proceedings of the Transportation Research Board 86th Annual Meeting, Washington DC, United States, January, 2007.

[4] J. Viegas, B. Lu, J. Vieira, and R. Roque, “Demonstration of the intermittent bus lane in Lisbon,” IFAC Proceedings Volumes, vol. 39, no. 12, pp. 239–244, 2006.

[5] H. Z. Dong and Y. T. Zhao, “Optimization of time division multiplexing for dedicated bus lanes based on PARAMICS,” Journal of Zhejiang University of Technology, vol. 40, no. 01, pp. 65–69, 2012.

[6] H. Z. Dong, C. X. Zhao, and F. J. Fu, “Sharing bus lanes: a new lanes multiplexing-based method using a dynamic time slice policy,” Proceedings of the Institution of Civil Engineers - Transport, vol. 174, pp. 1–38, 2018.

[7] J. Viegas and B. Lu, “Traffic control system with intermittent bus lanes,” IFAC Proceedings Volumes, vol. 30, no. 8, pp. 865–870, 1997.

[8] J. Viegas and B. Lu, “The Intermittent Bus Lane Signals setting within an area,” Transportation Research Part C: Emerging Technologies, vol. 12, no. 6, pp. 453–469, 2004.

[9] L. T. Truong, G. Currie, and M. Sarvi, “Analytical and simulation approaches to understand combined effects of transit signal priority and road-space priority measures,” Transportation Research Part C: Emerging Technologies, vol. 74, pp. 275–294, 2017.

[10] Y. L. Chang, Y. T. Dong, and P. Zhang, “Study on optimal control system of intermittent bus-only approach,” Science Technology and Engineering, vol. 15, no. 031, pp. 96–100, 2015.

[11] Y. Zeinali Farid, E. Christofa, and J. Collura, “Person-Based Evaluation of Dedicated Bus Lanes and Queue Jumper Lanes at Signalized Intersections with Near-Side Bus Stops,” in Proceedings of the Transportation Research Board 94th Annual Meeting, Washington DC, United States, August, 2015.

[12] S. Shu, J. Zhao, and Y. Han, “Novel design method for bus approach lanes with bus guidance and priority controls for prioritizing through and left-turn buses,” Journal of Advanced Transportation, vol. 2019, Article ID 2327876, 15 pages, 2019.

[13] J. Zhao and X. Zhou, “Improving the operational efficiency of buses with dynamic use of exclusive bus lane at isolated intersections,” IEEE Transactions on Intelligent Transportation Systems, vol. 20, no. 2, pp. 642–653, 2019.

[14] M. D. Eichler, Bus Lanes with Intermittent Priority: Assessment and Design, University of California, Berkeley, CA United States, 2005.

[15] M. Eichler and C. F. Daganzo, “Bus lanes with intermittent priority: strategy formulae and an evaluation,” Transportation Research Part B: Methodological, vol. 40, no. 9, pp. 731–744, 2006.

[16] W. Wu, L. Head, S. Yan, and W. Ma, “Development and evaluation of bus lanes with intermittent and dynamic priority in connected vehicle environment,” Journal of Intelligent Transportation Systems, vol. 22, no. 4, pp. 301–310, 2018.

[17] W. Hao, Z. Zhang, and Z. Gao, “Research on mandatory lane-changing behavior in highway weaving sections,” Journal of Advanced Transportation, vol. 2020, Article ID 3754062, 9 pages, 2020.

[18] H. Xie, J. Zhu, and H. Duan, “Analysis of the relationship between the density and lane-changing behavior of circular multilane urban expressway in mixed traffic,” Journal of Advanced Transportation, vol. 2022, Article ID 4499477, 40 pages, 2022.

[19] J. Ni, J. Han, and F. Dong, “Multivehicle cooperative lane change control strategy for intelligent connected vehicle,” Journal of Advanced Transportation, vol. 2020, Article ID 8672928, 10 pages, 2020.

[20] H. B. Zhu, “Numerical study of urban traffic flow with dedicated bus lane and intermittent bus lane,” Physica A: Statistical Mechanics and Its Applications, vol. 389, no. 16, pp. 3134–3139, 2010.

[21] A. Barri and S. Thajchayapong, “Detection and classification of traffic anomalies using microscopic traffic variables,” IEEE Transactions on Intelligent Transportation Systems, vol. 12, no. 3, pp. 695–704, 2011.

[22] L. Zhang, C. Chen, and J. Zhang, “Modeling lane-changing behavior in freeway off-ramp areas from the shanghai naturalistic driving study,” Journal of Advanced Transportation, vol. 2018, Article ID 8645709, 10 pages, 2018.

[23] V. Zyryanov and A. Mirchuk, “Simulation study of intermittent bus lane and bus signal priority strategy,” Procedia - Social and Behavioral Sciences, vol. 48, no. 1, pp. 1464–1471, 2012.

[24] F. Qiu, W. Li, J. Zhang, X. Zhang, and Q. Xie, “Exploring suitable traffic conditions for intermittent bus lanes,” Journal of Advanced Transportation, vol. 49, no. 3, pp. 309–325, 2015.

[25] D. Wu, W. Deng, and Y. Song, “Evaluating operational effects of bus lane with intermittent priority under connected vehicle environments,” Discrete Dynamics in Nature and Society, vol. 2017, Article ID 1659176, 13 pages, 2017.

[26] J. Viegas, R. Roque, and B. Lu, “The intermittent bus lane system: Lisbon demonstration project[1],” Public Transport International, vol. 56, no. 3, pp. 40–43, 2007.

[27] G. Currie and H. Lai, “Intermittent and dynamic transit lanes,” Transportation Research Record: Journal of the Transportation Research Board, vol. 2072, no. 1, pp. 49–56, 2008.

[28] L. Wright and W. Hook, Bus Rapid Transit Planning Guide, Institute for Transportation and Development Policy, New York, USA, 2007.

[29] M. J. Lighthill and G. B. Whitham, “On kinematic waves. II. A theory of traffic flow on long crowded roads[1],” Proceedings of The Royal Society a Mathematical Physical and Engineering Sciences, vol. 229, no. 1178, pp. 317–345, 1955.

[30] P. I. Richards, “Shock waves on the highway,” Operations Research, vol. 4, no. 1, pp. 42–51, 1956.

[31] B. Bian, J. Zheng, and B. Zhao, “Bus arrival time prediction based on RBF algorithm,” Modern Electronics Technique, vol. 43, no. 14, pp. 131–134, 2020.

[32] X. M. Chen, H. B. Gong, and J. N. Wang, “BRT vehicle travel time prediction based on SVM and kalman filter,” Journal of
[33] N. Zhang, H. Z. Dong, and Y. N. She, “Seq2Seq prediction of bus trajectory on exclusive bus lanes,” *Journal of Zhejiang University (Science Edition)*, vol. 55, no. 08, pp. 1482–1489+1517, 2021.

[34] X. Wang, X. M. Chen, and W. B. Kou, “A prediction model of bus dwelling time at the stops,” *Journal of Transport Information and Safety*, vol. 34, no. 02, pp. 55–61, 2016.

[35] X. Chen, S. Wu, C. Shi et al., “Sensing data supported traffic flow prediction via denoising schemes and ann: a comparison,” *IEEE Sensors Journal*, vol. 20, no. 23, Article ID 14317, 2020.

[36] X. Chen, H. Chen, Y. Yang et al., “Traffic flow prediction by an ensemble framework with data denoising and deep learning model,” *Physica A: Statistical Mechanics and Its Applications*, vol. 565, Article ID 125574, 2021.

[37] P. A. Lopez, M. Behrisch, and L. Bieker-Walz, “Microscopic traffic simulation using SUMO,” in *Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, pp. 2575–2582, Maui, HI, USA, November 2018.